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EXPERIMENTAL STUDIES OF MODEL COLUMNS

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I. INTRODUCTION

1. Object and Scope of Investigation

The performance of open section steel columns may be considerably influenced, among other factors, by (a) the distortion of the cross-section during lateral buckling, and (b) the presence of initial residual stresses. The influence of residual stress and of cross-sectional distortion on the behavior of the large-scale columns initially tested (1,2)* in this column research program are discussed in detail in the analytical studies presented in Progress Report No. 3 (3). The model tests reported herein were designed to investigate the validity of the assumptions made in this previous analytical work and also to confirm the conclusions contained in that report. Two independent series of tests were conducted; one series was related to the problem of flange rotation and the other to the problem of residual stress. Three models were tested in each series.

As discussed in the previous Progress Reports the flanges of the large scale columns twisted simultaneously with the lateral buckling. Progress Report 3 gives an analysis of the elastic behavior for this type of cross-section. The true buckling load is estimated and in addition upper and lower limits are determined, the upper limit based on the assumption that the web completely prevents relative rotation of the flanges and the lower limit based on

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* Numbers in parenthesis refer to references at the end of this report.

the assumption that the web has no power to resist relative rotation of the flanges. The ultimate load may then be estimated from the elastic buckling load and the stress-strain curve of the material. The first series of tests was undertaken to investigate the behavior of this type of open section column and to compare the results with the predictions of the analysis.

The first two models tested in this series were fabricated with different web thicknesses but with identical flanges which approximated (to a 1/12 scale) those of the 52-C series prototype columns. The model flanges were proportionally much stiffer torsionally than their prototypes since they had slightly greater wall thicknesses and in addition were each made from one solid, continuous piece (as opposed to the prototype flanges which were built-up from small elements). On the basis of analysis it would be expected that no appreciable distortion of the section would occur in these models and that the difference in their web thickness should not affect their ultimate stress. The test results appear to verify the theory for torsionally stiff flanges and long columns.

The behavior of model columns having flanges with torsional stiffness comparable to those of the full-sized specimens was next investigated. Because of shop limitations it was not possible to fabricate such members in the same manner used in preparing the specimens described above. Accordingly, a method was developed for fabricating models from sheet metal formed into plates and angles, and a third and more exact replica (1/6 scale) of the 52-C series of columns was prepared in this manner. However, the development of a series of tests using this type of model was interrupted due to the difficulty of obtaining the necessary material.

The analytical studies presented in Progress Report No. 3 indicated that there was a substantial reduction in the ultimate load of the 57-C series of columns because of the presence of initial residual stresses. Residual stresses are often induced in rolled sections as a result of non-uniform cooling after the rolling process, cold straightening, punching of holes, and riveting. In recent years residual stresses have been suspected of exerting an important influence on the strength of columns. However, the question still exists as to whether residual stresses are capable of lowering the ultimate load of a column. Available experimental evidence is not conclusive on this point. The assumption is commonly made that residual stresses (or strains) have the same effect on the stress-strain behavior of any fiber as the applied stresses (or applied strains) and that the two quantities are additive. The second series of small column tests was undertaken to supply additional information on this question.

A method has been devised whereby it is possible to introduce into model columns during their fabrication initial prestress of controlled magnitude and known distribution. In this manner the relation between residual stress and column strength can be studied.

Since this study was of a more fundamental nature the elaborate cross-sections used in the flange rotation investigation were replaced by a simple H-section. A total of three identical columns were tested in this study, one with initial compression stress in the flanges and tension stress in the web and two with no initial prestress. The moment of inertia of these columns was purposely made least about an axis parallel with the web so that the columns would bend in a plane normal to the web. Thus the flanges contributed practically all of the resistance against bending. If the aforementioned assumption is correct, the maximum total stress (prestress plus applied stress) in the flanges for all columns should be equal regardless of the initial prestress. Since there was a small variation in material properties between the identical specimens, however, the ratio of the maximum total stress to the yield point stress of the material is probably the best basis of comparison.

Although incomplete, the results of the study indicate that the assumptions previously made regarding the role of residual stresses in influencing the ultimate load of the large scale columns are essentially correct.

Because of the relatively small number of tests performed it is emphasized that the model studies reported herein should be regarded only as pilot investigations or exploratory tests.

2. Acknowledgement

The investigation reported herein was performed as part of a research program in tests of large steel columns sponsored by the Bureau of Public Roads, Department of Commerce and constitutes a portion of the Structural Research Program of the Department of Civil Engineering of the University of Illinois. This investigation was under the general direction of N. M. Newmark, Research Professor of Structural Engineering and under the direct supervision of W. J. Austin, Research Assistant Professor of Civil Engineering. The studies were performed in the Talbot Laboratory by P. Y. Chow and S. Cherry, Research Assistants in Civil Engineering.

II. INVESTIGATION OF COMBINED LATERAL BUCKLING AND FLANGE TWIST

3. Design and Preparation of the Models

A. Models MW-1 and MW-2

For the small scale studies the actual built-up section of the 52-C series columns was first simulated by models (designated as MW-1 and MW-2) having the simplified shape shown in Fig. 1. These specimens were prepared by forming the component sections in a milling machine after which the various elements were assembled.* This process imposes limitations on the length of the specimen and on the wall thicknesses of the flanges so that an accurate "simplified" scale model is not possible. In comparison with the overall dimensions, the flange wall thicknesses of the models were on the average somewhat greater than the value necessary for an accurate model replica. Although desirable, accurate scale models are not essential to a basic study of the problem.

The material composing the flanges was cut from 3/4 inch ASTM A-7 structural steel plate. The operational technique used in forming the flange sections in the milling machine is illustrated in Fig. 2. As indicated therein, pairs of flanges were prepared simultaneously and from the same bar stock. The material was first clamped to the milling machine table along recesses 1 and 2. Surface A was then milled plane and recesses 3 through 11 were cut as illustrated by the shaded area in the figure. Slots 3, 6 and 9 were cut down to the exact width of the outstanding flange leg (surface C) which was nominally 1/16 in.

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* A similar method of fabricating model columns has also been used by Professor J. F. Baker of Cambridge University, England in his column

below the other cuts (surface B). After completing steps 1 through 11 the plate was rotated 180 degrees about its longitudinal axis and surface D was then milled to surface C throughout the region indicated by the diagonal cross hatching. The waste material, which was used for control specimens, was removed merely by bending it along the junction to the flange corners. This technique avoided damaging the edges of the flanges.

The web plate of MW-1 was cut from 1/16 in. sheet material and milled to the proper size. Model MW-2 was made following MW-1 and its web thickness was reduced to 0.014 in. or approximately two-ninths of the web thickness of MW-1. Because of its extreme thinness this plate was not milled, but was cut to its proper length and width from the sheet material.

Solder was used to attach the flanges to the web. The component sections were assembled and clamped to a table across the column depth. Model MW-1 was heated over its entire length at the flange-to-web junctions by means of an acetylene torch. This allowed the wire solder which was applied in passes, to flow smoothly into and along the web slot, thereby giving a satisfactory joint. Since the web used with MW-2 was much thinner than the 1/16 in. groove in the flanges it was first wedged in and aligned along the center line of the slot by inserting into the slot and along both sides of the web plate steel filler strips of the proper thicknesses. A soldering iron was then used to attach the web plate and filler strips to the flanges of this model. The ends of the columns were milled plane and plane surfaced base plates were then attached using solder for MW-1 and weld material for MW-2.

The nominal cross-sectional dimensions of models MW-1 and MW-2 are shown in Fig. 3.

B Model MW-3

Following the tests of MW-1 and MW-2 a third and more exact replica (designated as MW-3) of the 52 series of large columns was fabricated from plates and angles such that the cross-sectional shape was identical with that of the full scale columns. A reduction factor of 1/6 was used in scaling MW-3 from the prototype. The resulting dimensions of the model are shown in the detail drawing of Fig. 4. The angles and flange plates were cut from 1/16-in. carbon-steel sheet material while the web was cut from 0.075-in. carbon-steel sheet material. Since it was impossible to procure angles of the desired size, the necessary sections were made by bending 1-in. wide steel strips into the proper shape. This procedure had the disadvantage that a sharp right-angled corner could not be obtained.

The plate and angle elements were connected with 1/8 in. soft iron rivets to form the complete column section shown in Fig. 4. This type of rivet was selected in order to facilitate cold driving which was done by hand. The 1/8-in. rivets are somewhat larger than the 1/6 scale reduction from the prototype rivets, so that the resulting relatively greater rivet strength was balanced somewhat by using a larger rivet spacing and the softer material. After the section had been assembled, the ends were milled plane and base plates were attached by welding. The outer face of each base plate was then milled to assure squareness of the ends.

4. Description of Measurements and Test Procedures

A. Strain Measurements

Strain and deflection measurements were obtained at various points along the columns. For MW-1 longitudinal strains were measured with SR-4, A-7, electric strain gages situated: (a) at the four corners of the flanges and on opposite faces of the web at each quarter section and (b) at 2-3/4 in intervals (measuring from the center section) along opposite edges of one of the flanges. The latter were used to aid in the study of the effective column length. The location of the strain gages at the various sections is indicated in Fig. 5.

The number of strain gages mounted on MW-2 was reduced and confined to the mid-section of the column. The locations of the gages were the same as those used on the corresponding section of MW-1.

Eight SR-4, A-7, electric strain gages were distributed over the center section of model MW-3. One gage was mounted at each corner of the section on the flange angle, one on each face of the web, and two additional gages on the north flange plate. Fig. 6 (c) shows the location at which these strain measurements were taken.

For all three tests the leads from the active SR-4 gages and also the single compensating gage which was used for temperature correction were carried to a central switching unit located near the base of the column.

B. Deflection and Flange Rotation Measurements

The initial crookedness of each model was determined by supporting the specimen as a beam and measuring the distance from a level surface to the column at various sections by means of a movable dial gage.

The deflections caused by the weight of the specimen were eliminated by taking a duplicate set of measurements with the column in the reverse position.

In the test of MW-1 only lateral deflections perpendicular to the plane of the web (the weak direction) were recorded (see Fig. 5 (b) directions 1 and 2). These movements were detected by a series of Ames dials attached to a fixed bracket. As indicated in Fig. 5, the plungers of these dials were made to engage one corner of each flange at each of the three 1/4-sections. In addition to the lateral deflection measurements described above, deflections parallel to the plane of the web (the strong direction) were also taken at these sections during the tests of MW-2 and MW-3. These movements were measured at diagonally opposite flange corners as indicated in Fig. 6 (c). This arrangement was adopted in order to obtain sufficient data for evaluating the rotation of the flanges.

For column MW-1 measurements of overall column shortening were obtained at the four corners of the model with a movable compressometer using a 32-in. gage length. In the tests of MW-2 and MW-3 this instrument was replaced by deflectometers which were located on each side of the column and which measured the change in distance between the machine heads.

A 2-in. pointed micrometer which measured the distance across the depth of the column at the flange corners was used to detect the relative twisting of the flanges at each 1/4 section of MW-1 and each 1/8 section of MW-2 (see Fig. 5 (b) directions 3 and 4). The number of readings were increased in the second test since it was anticipated that a more pronounced flange movement might occur with this model. A caliper-type instrument containing a mechanical dial was used to measure the movement of the flanges of MW-3. The ends of the calipers were fitted with small knife edges which, for purposes of measurement, were inserted into notches cut into the edges of the flange toes at eight sections of the column.

The test set-ups used for the models of this series are shown in Fig. 7.

C. Test Procedure

The tests of MW-1 and MW-2 were conducted in a Baldwin hydraulic testing machine of 120,000 lb. capacity; MW-3 was tested in a 300,000 lb. Riehle screw-type machine. The models were tested flat-ended, each end bearing on a steel disk which was rigidly supported against rotation. The lower disk was set within the concentric rings inscribed on the testing machine table while the upper disk was rigidly clamped to the movable head of the machine in alignment with the lower disk. The column was centered with the aid of concentric circles marked on the disks. The movable head of the testing machine was lowered until contact was just made with the column base plate. Brass shims were then inserted between any gaps which existed between the steel disks and the base plates. Strain gage readings for the first increment of load showed that these measures gave an axial condition of loading.

For columns MW-1, MW-2, and MW-3 the first sets of readings were taken at initial loads of 200 lb., 320 lb., and 700 lb., respectively. Load increments of 1000 lb. were applied to the smaller columns and 3000-4000 lb. to the larger column. Near the ultimate load these increments were varied as suggested by the results obtained. In all cases the load was applied continuously to failure; strain and deflection readings were taken after each increment of load up to the maximum load.

D. Material Coupon Tests

The mechanical properties of the material used in the models were determined from tensile and compression coupon tests. Tensile coupons were obtained from the waste material removed from the flanges of models MW-1 and MW-2, from the sheet material used for the web of MW-1, and from the sheet and strip material used in fabricating MW-3. The tensile specimens were machined according to ASTM standards (based on a 2-in. gage length). Compression coupons were also obtained from the flange waste material of the smaller models and were machined so that their lengths were four times their least dimension (their thickness) and their widths were two times their least dimension.

After model MW-1 had been tested to failure a 3 in. length was cut from the column (1/2 in. from the top end) and this section, in its entirety, was tested in compression. The results of this test and those of the coupon tests are presented in Table II.

5. Results and Discussion of Tests

A. Model MW-1

(i) Deflection Data

The lateral deflections of the south and north flanges at various stages of the test are plotted in Figs. 8 and 9 respectively. These curves show the true deflection shape of the model in a direction perpendicular to the plane of the web (the weak direction). The zero load deflections which are the initial crookedness were taken at nine points along the length of the column in the manner described in section 4B and indicate that before the model was loaded the maximum deviation (in the weak direction) of its axis from a straight line was 0.007 in. The data show that at a load of 1000 lb. the deflected shape of the south flange was essentially equal to its zero load condition while the north flange had deflected approximately 0.005 in. toward the west. At higher loads both flanges deflected steadily toward the east, eventually resulting in failure of the column. The reversal in direction of deflection of the north flange after 1000 lb. was probably due to the influence exerted by the south flange which just began to deflect eastward after this load was reached. The individual curves are essentially symmetrical about mid-section.

A further study of the bending behavior of the column is given in Fig. 10 which presents curves of average deflections of the north and south flanges vs. the load. Starting at 9000 lb. the slope of the curve commenced to decrease progressively with increase of load.

The curve of Fig. 11 represents the relation between the load and the average of the compressometer measurements taken at the four corners of the column. With the exception of some slight scatter at the lower loads, the average overall shortening curve is a straight line up to a load of 11,500 lb. after which it begins to level off rather sharply, indicating that yielding started at approximately this load.

As previously explained, because of the limitations imposed in scaling the model its torsional stability was greater than that of the prototype. This was evident from the experimental results which indicated that there was no rotation of the flanges throughout the entire test.

(ii) Strain Data

Fig. 12, which presents the results of the strain measurements taken with the four SR-4 gages located at the flange corners of the mid-section (see Fig. 5 (b)), represents a typical set of load-strain curves. The strain on the concave side of the column increases fairly uniformly until lateral bending becomes significant and then increases rapidly with small increments of load. On the convex side of the column, as the lateral bending increases, the tension strain due to bending (which proceeds simultaneously with increasing axial load) counters the compressive strain due to axial load resulting (near ultimate load) in a decrease in strain with an increase of the load.

The curve of load vs. the average of the measured strains at three sections of the column is shown in Fig. 13. This curve is linear up to a load of about 10,000 lb. and then the slope of the curve very gradually decreases until near ultimate load where a sharp break occurs. Thus yielding appears to have begun at a load of about 10,000 lb. However, in the discussion of the load - overall shortening curve it was estimated that yielding began at about 11,500 lb. The strain measurements are probably more sensitive than the overall shortening measurements, and accordingly the former value for the load at the initiation of yielding is probably the more accurate of the two. The linearity of both curves up to high loads leads to the conclusion that only negligibly small initial residual stresses could have been present in model MW-1. The average modulus of elasticity for the entire column based on the linear portion of the curve in Fig. 13 is 30.5×10^6 psi; this value is very nearly equal to the average coupon value of the modulus of elasticity of 30.3×10^6 psi.

(iii) Curvature Plots

The SR-4 gages applied in pairs at eleven sections along one of the flanges of the model were used to determine the column curvature in the same manner as described for the full scale prototypes (3). The curvatures along the length of the column for five loads are plotted in Fig. 14. These curves indicate that there was only a single point of inflection in the column, occurring in the vicinity of the 3/4 section. This point tended to move toward the top of the column as the load was increased such that the final recorded location was approximately 6.4 in. from that end. The plots suggest that the curvature tends to zero at some point within the lower 2 3/4 in. region of the column, thereby indicating that the restraint offered at this end was essentially zero. After the test was concluded it was noticed that the base plates had separated from the columns at both ends; the solder joints had failed during the test. This action probably reduced the end restraint. Apparently there was no restraint at the base, but there was some small restraint at the top, as shown in Fig. 14. The effective length of the column on the basis of the curvature plots is 26.6 in. which is 81 per cent of the overall column length.

(iv) Critical and Ultimate Load

An estimate of the critical column load was made by means of the Lundquist method (3). The results of these calculations are presented in Fig. 15. Three plots were made using initial loads of 2000 lb., 4000 lb., and 6000 lb., yielding critical loads of 15,000 lb., 15,610 lb., and 15,730 lb., respectively, or an average value of 15,450 lb. If the values of the effective column length and the average elastic modulus are set into Euler's theoretical expression the resultant elastic critical load becomes 16,460 lb., which exceeds the estimated value by 4.65 per cent. Since the points through which the curves of Fig. 15 are drawn correspond to a load range in excess of 9000 lb. and as such are based on probably partially inelastic deflection data it would be expected that the estimated critical load should be less than the theoretical critical load. This is in agreement with the findings.

The ultimate load carried by the model was 13,450 lb., which is equivalent to an average stress of 37,700 psi., or 96.1 per cent of the average material yield point obtained from the tension and compression coupons.

B. Model MW-2

(i) Deflection Data

The true deflected shapes of the individual flanges are shown in Fig. 16 for several loads. Although the individual flanges deflected in opposite directions over a large range of the test, at failure the column as a whole deflected northward. At low loads both flanges deflected in a very slight S-shape. As the load was increased this tendency became more pronounced. With the west flange most of the movement took place at the lower 1/4-section. On the other hand, with the east flange most of the movement occurred over the upper region of the column. The difference in bending behavior of the two flanges was probably largely due to the inability of the highly flexible web to force the flanges to deflect in the same direction.

Curves of the lateral deflections (averaged for the two flanges) vs. the load for the one-quarter, mid-height, and three-quarter sections are presented in Fig. 17. Neglecting the early irregularities, these average deflection-load curves were linear up to a load of approximately 8000 lb. after which the deflection increased rather rapidly with the load. The S-shaped deformation of the column for loads less than 7000 lb. is indicated clearly in this figure which shows that the mid-section did not deflect until after this load had been reached.

Curves which illustrate the flange-rotation behavior of MW-2 are shown in Figs. 18 and 19. The flange rotations were computed from the micrometer readings and deflection measurements in the direction parallel to the plane of the web; for this computation the flange section was assumed to maintain its original shape.

Fig. 18 illustrates that there was no pronounced rotation of the flanges; the angular movement of the east flange accounted for almost all the rotation which occurred. The rotation of this flange at the three sections varied linearly with the load and amounted to approximately 0.0015 radians for each 2000 lb. load increment. The maximum recorded rotation occurred at the mid-section and was approximately 0.008 radians. Neglecting initial irregularities, the load-rotation curves of the west flange are practically vertical throughout the entire range of recorded data indicating that this flange did not exhibit any appreciable angular rotation. Although no micrometer data were obtained at the ultimate load the direction of flange rotation for loads greater than 9000 lb., based on the observed failure condition of the model, is indicated on the figure.

The graphs of the change in the distances between the flange toes at each 1/8-section of the model presents another picture of the flange-rotation tendency. From Fig. 19 it may be noted that, in general, slight and consistent changes in the distance between flanges occurred only after a load of 6,000 lb. had been reached. The relatively large movement which occurred on the north side of the 1/2-section immediately after the first load increment is probably due to a change or error in the initial "zero-load" reading. It was noted by observation that once the ultimate load had been reached the resulting excessive lateral deflection was accompanied by a rapid rate in increase of the angular flange rotation.

The average curve of the overall shortening measurements is plotted in Fig. 20. Although this curve is influenced by the deformations of the loading blocks and shims, etc., it nevertheless serves to indicate the beginning of general yielding. From the figure it appears that this condition occurred in the vicinity of 8000 lb. which is the load at which the curve departs from linearity.

(ii) Strain Data

Strain-load curves based on the average strain measurements obtained from the electric SR-4 gages located on the flanges and on the web at the mid-section of the model are plotted in Fig. 21. The curves of the average web strains and average flange strains are in close agreement at low loads indicating that these elements of the section carried their proper proportion of the total column load over this range (0-4500 lb.). However, at 4500 lb. the web strains departed from the initial linear load-strain relation; this deviation increased rapidly thereafter until a load of 7000 lb. was reached after which no further increase in web strain resulted from an increase in load. This indicates that the center portion of the web had buckled elastically "out of the way" and therefore no longer carried any proportion of the subsequent increase of the column load. This phenomenon was corroborated by visual observation of the buckling of the web plate into waves along its length. The condition first became noticeable over the upper half and extreme lower region of the model at a load of 6000 lb. By 7000 lb. the web had buckled into waves along its complete length. The half wave lengths were approximately equal to the unsupported width of the web.

In Fig. 21 the slope of the load-average flange strain curve decreases for loads above 6000 lb. This behavior should be expected because the load increments above the load at which the web buckled were probably carried almost completely by the flange area alone. It seems impossible to separate this effect from the effects of yielding which also cause a decrease of the slope of the curve. Therefore, the beginning of yielding cannot be predicted from this curve. However, the individual strain gage readings of the flange gages (not reported) did not show the existence of strains large enough to induce yielding until a load of about 9500 lb. was reached.

(iii) Ultimate Load

The maximum load carried by this model was 10,000 lb. This corresponds to an average stress on the gross section of 35,900 psi or 89 per cent of the average material yield point obtained from the tension and compression coupon tests. However, the web buckled under a total column load of about 6000 lb.; of this load approximately 380 lb. was carried by the web. If the web is assumed to be incapable of carrying any portion of subsequent load increments above this level, the maximum load carried by the flanges is 9620 lb., which corresponds to a stress of 37,000 psi or approximately 92 percent of the average coupon yield point stress.

C. Model MW-3

(i) Deflection Data

The deflected shape of each flange of Model MW-3 (in the weak direction) at various loads is illustrated by the plots shown in Fig. 22. As a result of riveting, bending of the flanges, etc., many local irregularities were introduced into the surfaces of the plate elements so that an accurate determination of the original shape of the model at zero load could not be obtained. The deflections shown in Fig. 22 were therefore plotted relative to the deflected position at a load of 700 lb. In spite of the local irregularities mentioned above, the column as a whole appeared to be fairly straight and the magnitude of the initial deviations seemed to be smaller, proportionately, then the 52-C series prototypes. It should be noted that throughout the test the lateral movement of the south flange lagged that of the north flange by a considerable amount.

Continuous lateral deflection - load curves for each quarter section of the column are presented in Fig. 23. Each point represents the average deflection of the two flanges. These deflections increased slowly for loads below 30,000 lb. Subsequent load increments above this level resulted in rapid increases in the deflection.

The change in the distance between the flange toes corresponding to successive load increments is shown in Fig. 24 at various sections along the column. This diagram indicates that a definite movement of the flanges accompanied the lateral bending of the column.

In general the movement began to develop after 20,000 lb. had been applied to the model. The most pronounced flange rotation occurred in the general vicinity of the mid-section of the column.

It is desirable to compare the results of the lateral deflection and flange rotation measurements for MW-3 and the prototype columns 52-C-1 and 52-C-2 in order to determine whether the model duplicated the behavior of the large columns. In making this comparison the deflections of the full-sized members have been reduced by the 1/6 model scale-factor. The resulting curves for the center sections of the specimens are presented in Fig. 25 (a) and (b). From the curves of average lateral deflection (Fig. 25 (a)) it may be noted that the model was much stiffer than its prototypes. On the other hand, the average relative rotation of the flanges of the model was of the same order of magnitude as the corresponding curves for the 52-C-1 and 52-C-2 columns. This suggests that, in relation to the bending stiffness, the torsional stiffness of the model was less than its prototypes. This may be due to the fact that, because of the type of end bearing blocks provided, model MW-3 was probably restrained to a greater extent than the columns of the 52-C test series and as a result the effective length of this model was comparatively less than the effective lengths of the prototypes. As discussed in Progress Report No. 3, for the cross-sectional proportions of the columns under consideration this would increase the tendency towards a flange-twist movement.

(ii) Strain Data

The curves of Fig. 26 represent the average strain in the various column elements as obtained from the gages situated on (1) the flanges at the four corners of the column and the web plate and (2) the north flange plate.

For loads less than 32,500 lb. the deviation of the individual strain measurements used in plotting the average curve of the 4 flange angle and 2 web plate gage data is negligible. Above this limit the web strains increase more rapidly than the flange strains. From the diagram it may be seen that the average curve for the six gages agrees closely with a theoretical curve computed on the basis of the gross area and on a weighted elastic modulus of the angles and web.* The former curve increases linearly until a load of 20,000 lb. is reached after which there is a gentle and continuous increase in its curvature.

Over the complete load range, the average flange plate strain was greater than the total average strain in the flanges and web of the model. This may be due to the fact that these gages were mounted between rivet lines and therefore were in a region of high stress concentration.

The early yielding noted even at relatively low loads is probably due to manner of fabrication of this model. The manufacturing process required that a large number of rivet holes be drilled through

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* The moduli of elasticity and yield point test results for the tensile coupons of the various component elements of the section were weighted according to the area of the component elements in proportion to the total area of the cross section.

the flange angles, flange plates and web. Such holes are points of stress concentration which cause a local yielding in their vicinity. In addition, in fabricating MW-3 it was necessary to use a number of plate elements to form the column section. It may be noted from Table II that there was a large variation in the material properties of these different elements. Variations in the material yield point and elastic modulus influence the shape of the load-strain relation of the column as a whole. Thus, the flange plate material which had a yield point and an elastic modulus considerably below that of the remaining material would be expected to yield at an average stress below that required for general yielding of the entire column.

(iii) Critical and Ultimate Load

The ultimate load carried by this column was 40,000 lb. This amounts to 37,100 psi or 94.5 percent of the weighted material yield point obtained from the tensile coupons.

An initial load of 21,000 lb. was used as the basis of the deflection data for the Lundquist plot shown in Fig. 27. This load corresponds to the beginning of a stiffness reduction of the column. Accordingly, since the curve was fitted to points which were at least partially in the inelastic range the resulting graph should give an estimate of the ultimate strength rather than the theoretical critical load of the column. The resultant estimated ultimate of 40,900 lb. agreed very closely with the 40,000 lb. load obtained experimentally.

Photographs of the three columns of this series after failure are shown in Fig. 28. The deflected shapes have been accentuated since the columns were loaded after they had failed until large deflections were produced. During the failure of MW-3 a local crippling of the flanges at midsection was noted. A picture of this crippling failure is given in Fig. 30 (d). It is not known whether this local buckling caused the failure or whether it is a result of the failure.

III STUDY OF THE EFFECT OF RESIDUAL STRESSES ON ULTIMATE LOAD

6. Preparation of the Specimens

A. Design of Models

The simplified H-type section shown in Fig. 29 was used in evaluating the effect of residual stresses on the behavior of columns. Although not representative of the large columns originally tested such specimens are nevertheless satisfactory for a basic study of the problem and also are preferable since they can be rapidly and easily produced.

All three specimens (designated as models MR-4, MR-5, and MR-6) discussed in this section were formed in the same manner and had the same nominal dimensions. The flanges and web were cut from 2 x 1/8 in. structural steel bar material and then milled to the proper width. A 1/8 x 1/16 in. slot was milled along the center line of one face of each flange and the edges of the web plate were subsequently fitted into these grooves during the fabrication operation. In order to reproduce a consistent set of end conditions knife-edge bearing supports were adopted for all models tested in this series. (See Fig. 30). These blocks were attached to the base plates of the specimen by means of a pair of screws which were tapped into the knife-edge blocks and fitted through holes in the base plates to which they were clamped by means of nuts as illustrated in Figs. 29 and 30. Although the total distance between knife edges was nominally 28 in. the actual free length of the column between base plates was approximately 25 in. When the distance between knife edges is taken to be the effective length, the l/r ratio of each specimen is 83.3. A correction to the l/r ratio to account for the effect of the rigid blocks at each end of the column may be made as proposed by Osgood (4). In this case the correction amounts to only 0.3 per cent.

In order to compare accurately the behavior of the stress-free and prestressed models it was necessary to fabricate and connect the elements comprising the column sections in the same manner. As discussed below, the connection procedure adopted was governed by the method used to introduce artificial prestress into the specimens. Accordingly, the fabrication method of the stress-free models MR-4 and MR-6 was dependent upon that used for prestress model MR-5.

B. Method of Prestress and Fabrication

The technique developed for introducing residual stress into the model is essentially a strain transfer-relaxation process. Before assembling the plate elements of the section the web (whose length was initially cut 10 in. oversize) of the model was centered between the grips of a 120,000 lb. hydraulic testing machine and stressed to approximately 87 per cent of the material yield point. A synthetic resinous compound known commercially as Cycleweld C-14* was then applied into the grooves of the flanges and along the edges of the web plate while the web was still in position in the testing machine and the initial load level was maintained, the flanges were fitted along the web and

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* It was necessary to avoid the use of solder along these junctions since the SR-4 gages mounted to record induced prestress might otherwise have been affected by the excessive heat generally required for this manner of connection.

clamped into position by means of adjustable, right-angled clamps of the type shown in Fig. 31. Since the cycleweld is a highly viscous liquid which does not immediately set all the load was still being carried by the web element; the flanges were strain-free at this stage of the operation. A 1 1/2 x 3/16 in. fillet weld strip was then applied to the web-flange junctions at each end of the column. As a result of the heat expansion of the material some of the initial web load was lost during this second stage of the prestress procedure. After the weldment had cooled the web plate was unloaded in stages. As the load was removed the relatively stress-free flanges restrained the relaxation of the web and as a result some of the load was transferred into the flanges. Upon complete release of the load a column with a self-equilibrating system of internal stresses was obtained. The specimen was then removed from the testing machine and the cycleweld was allowed to cure for eight days in order to develop its full strength. At the end of the curing period the over-sized lengths of the web were removed and the section ends were milled plane. Plane surfaced base plates were then welded to the columns. Any warping of these plates due to the welding was eliminated by further planing.

The amount and distribution of the prestress was determined by strain gages originally mounted on the flanges and web plate at the three 1/4-sections of the column <u>before</u> the section elements were assembled. Complete sets of strain readings were taken before and after the web was stressed, after the flanges were clamped into position and during the unloading process. The results of these measurements are discussed in detail later in this report.

The fabrication procedure of the two stress-free models was identical with that used for MR-5. In these cases, since no prestress was applied to the webs their lengths were originally cut to the proper dimensions. In order to obtain comparative specimens weld strips were also used to connect the ends of these models.

7. Description of Measurements and Test Procedures

Strain and deflection measurements were taken at various locations along the lengths of the models. The methods by which such measurements were obtained and the location at which these measurements were taken are outlined below. Reference should also be made to Fig. 32 which shows the location of the various measuring instruments and Fig. 33 which shows the typical testing arrangement for this series of tests.

A. Model MR-4 (Stress-free)

(a) Strain: Six SR-4, A-7 electric strain gages at the mid-section; one at each of the four corners of the flanges and one on each side of the web plate. These gages were mounted after the model had been fabricated.

(b) Deflection: Six mechanical dials for measuring the lateral deflection of the flanges in the weak (N-S) direction; one on each flange at the three 1/4-sections, located at diagonally opposite corners of the model.

Models MR-4 and MR-6 were both tested in the stress-free condition. The latter was a duplicate of the former and was tested to clarify the results obtained for MR-4 which was loaded eccentrically by accident.

B. Model MR-6 (Stress-free, Repeat)

(a) Strain: Four SR-4, A-12 electric strain gages mounted at the 1/2-section of the model; one on each of the four corners of the flanges. These gages were mounted after the model had been fabricated.

(b) Deflection: Two mechanical dials at the 1/2-section of the model for measuring the lateral deflection of the flanges in the weak direction; one on each flange at diagonally opposite corners.

C. Model MR-5 (Prestressed)

(a) Strain: A total of 48 SR-4, type A-12 electric strain gages were mounted on this model; 5 on each flange and 6 on the web at each 1/4-section, distributed in the manner shown in Figs. 32 and 43. This extensive series of measurements was taken in order to ascertain the magnitude and distribution of the induced residual stresses at each section and their variation between sections. These gages were mounted on the various elements of the section before the model was fabricated.

(b) Deflection: As for MR-4

A single compensating strain gage was used in each of the three tests. All SR-4 leads were carried to a central switching unit. In addition to the measurements described above, data of the flange rotation, lateral deflection in the strong direction, overall shortening and knife-edge rotation were also obtained. However, only the most significant results have been reported herein.

D. Centering and Testing of Specimens

The top grooved knife-edge recess was fastened to the moving head of the testing machine by means of a steel loading disk and centered with the aid of the concentric rings inscribed thereon (see Fig. 33). The bottom knife-edge recess was then aligned with the upper block and rigidly clamped to the testing machine table by means of the 1/4 in. steel strips which may be noted in the figure. The knife-edges were then lightly connected to the column base plates and the model was set between the recess blocks. A small load was applied to the column in order to permit the knife-edges to make continuous contact with their respective recesses. Any gaps which opened between the base plates and knife-edge blocks during the adjustment process were shimmed with thin sheet metal material and the knife-edges were then firmly clamped to the base plates. A load was next applied to the model and the SR-4 strain gages located at the 1/2-section were checked for bending. With MR-4 this check was only made at a low load (1,000 lb.) and although there was no variation among the gages at that level it was later found that a definite strain variation took place with subsequent load increases, thereby indicating an eccentric loading. With MR-6 and MR-5 the column position was initially adjusted such that there was a negligible strain deviation at 10,000 lb. and 5500 lb., respectively.

All three tests were conducted in a Baldwin hydraulic testing machine of 120,000 lb. capacity. After the models had been centered small initial loads were applied and a complete set of deflection and strain readings were taken and used as the base condition or reference for subsequent measurements. A 1000 lb. load was used as the base for MR-4 and load increments of 3000 lb. were then applied until a total load of 10,000 lb. was reached after which 2000 lb. increments were added until failure. An initial load of 500 lb. and increments of 2000 lb. were used with model MR-5. This same initial load was used with MR-6. When 16,000 lb. was reached the loading increment of MR-6 was reduced from 2000 lb. to 1000 lb. until failure took place. In all cases the loads were applied continuously to failure.

E. Material Coupon Tests

Tensile control specimens were removed from the bar stock material adjacent to the lengths from which the elements of the column sections were cut. Two sets of these specimens were tested. The first set was taken from material used in the fabrication of MR-4 and MR-5 whose elements were cut from the same bar stock. The second set was removed from the bars used in the manufacture of MR-6 only which was fabricated and tested after the tests of MR-4 and MR-5 had been completed. All coupons were machined according to the ASTM standards for 2 in. gage lengths. The results of these coupon tests are presented in Table II.

8. RESULTS AND DISCUSSION OF TESTS

A. Model MR-4 (Stress-Free)

(i) Deflection Data

The average deflected shapes of the model at various loads are shown in Fig. 34. These configurations are plotted relative to the shape at the initial 1000 lb. load which is considered as the base or zero line. Each point on the curve represents the average of the two gage measurements which were taken on the flanges at each 1/4-section of the column. The deflected shapes are symmetrical about the mid-height of the member and they indicate that there was a rapid increase in the rate of deflection when loads greater than 16000 lb. had been applied to the model. This is more clearly illustrated in the plot of Fig. 35 which represents the continuous average deflection-load variation of these sections of model MR-4. The slopes of the curves decrease rapidly with small load increments above 14,000 lb. and approach a horizontal line after a total load of 17,000 lb.

Flange opening and closing movements were found to be negligible as might be expected for a column with this cross-section.

(ii) Strain Data

Strain-load curves for gages located at the mid-height of model MR-4 are presented in Fig. 36. Individual curves for each gage located on the flanges and an average curve for all six gages on the section are given. The flange gages were attached about 1/8 in. from the edge of the flange. Therefore, these gages do not indicate the strains at the extreme outer fibers of the specimen; the maximum (or minimum) strains can be computed by increasing (or decreasing) the strains due to bending by 20 percent.

Bending in this column is indicated by the deviations of the load-strain curves for flange gages 2 and 4 on the north side of the column from the curves for gages 1 and 3 on the south side. These curves separate from the beginning of loading, the separation continually increasing as the load increases. At about 16000 lb. the strains on the south side begin to decrease because the tensile strains due to lateral bending begin to increase at a greater rate than the average compressive strains. On the north side where the bending strains are compressive the strain in the outer fibers considerably exceeds the average strain. Thus (in Fig. 36) at 16,000 lb. the average strain is only 800 micro-in per in. (24,000 psi based on $E = 30 \times 10^6$ psi) but the maximum strain indicated by gages 2 and 4 exceeds 1000 micro-in per in. Finally, yielding of the fibers on the north side caused failure of the column. The early bending in this column was caused by a slight eccentricity of loading. The final two columns of this series were centered more carefully and consequently very little bending occurred until near ultimate load when yielding commenced.

The curve of average strains for all six gages vs. the load in Fig. 36 is linear for loads less than 15,000 lb. Beyond this level there is a more rapid increase in strain with corresponding increments in load indicating yielding. The yielding increased in extent with increasing load. The linear portion of this curve agrees fairly closely with the theoretical load-strain relation based on the average modulus of elasticity obtained from the tensile coupons (30×10^6 psi).

Ultimate Load

The maximum load carried by Model MR-4 was 17,500 lb. The average stress at failure was 28,600 psi, which is 76 percent of the average tensile yield point stress determined from coupon specimens. As discussed above, the ultimate stress was lowered by an unintentional eccentric loading. The results of this test cannot be used for comparison with the subsequent column tests which were made with concentric loading.

B. Model MR-6 (Stress-Free, Repeat)

This model was a duplicate of MR-4 and was tested to determine the ultimate strength of the stress-free model when loaded concentrically. Accordingly, the knife-edge blocks were carefully adjusted so that at 10,000 lb. there was no appreciable deviation among the individual strain gage readings at the flange corners of the 1/2-section. The load was then reduced to 500 lb and this level was used as a base for deflection and strain measurements. Subsequent loading indicated that this axial condition was closely maintained for a considerable load beyond 10,000 lb.

(i) Deflection Data

The average deflection-load variation at the 1/2-section of MR-6 is presented in Fig. 37. This curve represents the average of the deflections taken on each flange of the model at this location. It may be noted that relatively large deflections occurred at low loads (0-5000 lb). However, as discussed below, the strain readings indicate that there was no bending over this region so that this deviation is possibly due to small adjustments in the loading blocks. Neglecting these irregularities it may be seen that over the major portion of the test the lateral deflection of the specimen was of a very small amount totalling approximately 0.001 in. at 16,000 lb. For loads greater than 16,000 lb. there is an increase in the deflection rate. It should be stated that this model and also its prestress companion failed suddenly and without much warning.

(ii) Strain Data

The load-strain curves shown in Fig. 38 (a) indicate that very little bending took place before the column failed; at 97.6 percent of the ultimate load the maximum strain deviation between the individual gages was only on the order of 10 percent. The average of all four curves (Fig. 40 (b)) varies linearly up to approximately 16,000 lb. after which there is a gradual decrease in the slope. Below this limit the average experimental result is in close agreement with the theoretical plot (based on an average modulus of elasticity of 30.4×10^6 psi as obtained from the tension coupon tests).

(iii) Ultimate Load

The ultimate load carried by model MR-6 was 20,500 lb. For this column the ratio of the average failure stress (33,700 psi) to the material yield point stress (36,400 psi) is approximately 0.93, which is considerably higher than the 0.76 value obtained for model

MR-4, and which is in the range to be expected. Model MR-6 was undoubtedly nearly axially loaded; with an even closer alignment the ultimate load would probably have been further increased.

C. Model MR-5 (Prestress)

(i) Initial Stresses

The results of the prestressing operation described in section 6B are presented in Figs. 39 and 40. The first figure shows a complete picture of the final residual strain distribution over the elements of the model section. In general there is good agreement between the strains on the inner and outer faces of the flanges indicating that the distribution through the thickness over these areas was very nearly constant. On the other hand, there is a considerable deviation between the strains on opposite faces of the web. However, the final strain difference between web faces was very nearly equal to the variation originally existing when the web was first stressed to approximately 87 percent of its yield point. This condition is evident from the web curves of Fig. 40 and possibly results either from an imperfect alignment of the heads of machine or an initial crookedness of the plate. At any rate, since it is the flange strains which are significant, these web strain variations are not an important factor influencing the behavior of the model. Only five strain measurements were obtained on the 3/4-section of the web of MR-5. The connection of the sixth gage originally mounted at this location was found to be defective. On the basis of the curves in Fig. 39, it may be concluded that the strain distribution in the flanges over any cross-section and along the model length was quite uniform (with a possible exception in the immediate vicinity of the weld strips at each end).

Although the compressive strain distribution in the flanges at the various sections of the model do not represent the actual conditions existing in rolled sections they are nevertheless satisfactory for a basic study of the problem and for purposes of analysis are advantageous since they provide a simplified stress block.

Fig. 40 provides a complete picture of the average strain-load variation on each face of the web and the flanges at the 1/2-section of the model during the unloading phase of the prestress operation. The curves for the 1/4 and 3/4-sections are similar to these curves for the 1/2-section. The plots of each flange curve are an average of two or three gage readings depending on whether they represent the strains on the interior or exterior faces of the flanges respectively. The plotted points for the web curves are an average of the three gage measurements taken on each web face.

Since the curves of Fig. 40 are unloading curves, the initial conditions are represented by the strains at the applied load of 8,000 lb. At this time the web carries the load; the flanges are unattached. During the welding of the flanges to the web plate there was a load drop of approximately 2000 lb. and an accompanying strain change in the elements of the section; the variation of strain with respect to load during the welding was not determined and is represented in the diagram by broken lines. Note that a small tension strain was introduced into the flanges during the welding operation. Subsequent decrease of the applied load resulted in a linear compressive strain increase in the flanges and a linear tensile strain decrease in the web with a definite residual strain remaining in these elements at zero load. The average strain-deviations between the surfaces of each flange and between the flanges themselves were small. The reason for the large discrepancy across the web thickness has already been explained.

At the mid-height of the column the average strain in the flanges was 240 microinches per inch (compression) while the value for the web was 345 microinches per inch (tension). The corresponding pre-stresses were 7170 psi and 10,350 psi, respectively. These stresses yield forces over the model section which are in statical agreement to within 3 percent.

(ii) Deflection Data

This specimen was initially centered so that under a load of 5,500 lb there was no appreciable deviation between the strain gages mounted at the four flange corners of the 1/2-section. The centering load was then reduced to 500 lb which was used as the base for deflection and strain measurements.

The continuous lateral deflection-load curves for the three sections of this column are shown in Fig. 41. The plotted points are the average of the two gage measurements taken on each flange of the respective 1/4-sections. The curves indicate that during the early state of the test the column deflected towards the north. At 8000 lb. there was a reversal in the direction of deflection such that at failure the column buckled southward. It should be noted, however, that the magnitude of these initial movements was only of the order of 0.001 in. Since the strain gages at the center section did not indicate any bending, these early deflections could possibly be due to a slight movement of the gage pointers over the flange surfaces. Of significance is the sudden break in the slope of the curve before failure which indicates that the column buckled southward very suddenly.

(iii) Strain Data

The average strain at the four corners of the flanges at the mid-section of MR-5 is plotted as a function of the load in Fig. 42 (b). Each point represents the average of the two corner gages; one located on the inner and one on the outer flange face. These curves indicate that for the greatest portion of the test the bending was of a small amount; the maximum deviation between the individual strain readings at 90 percent of the ultimate load was of the order of 10 percent. For the range of recorded strains the graphs show that the flanges deflected in opposite directions. However, at failure both of these elements deflected in the same direction.

In general there was close agreement between gages mounted on opposite faces of the flanges at the same distance from the bending axis and also between gages mounted on the opposite faces of the web. This suggests that very little localized bending of these individual elements took place.

The average of the forty-eight SR-4 gage strain measurements is plotted as a function of the load in Fig. 42 (a). This curve varies linearly up to 15,000 lb. after which there is a very slight decrease in slope up to failure, thereby indicating that the lateral buckling took place almost instantaneously. The experimental results are seen to agree very closely with the theoretical strain curve based on the average elastic modulus of 30×10^6 psi as obtained from the tensile coupon tests.

(iv) Ultimate Load

The ultimate load carried by model MR-5 was 17,700 lb. Neglecting the initial residual stresses which were introduced into this specimen the ratio of the average stress at ultimate load (28,600) to the average material yield point stress (37,740) was only 0.74. This ratio is considerably less than that obtained for column MR-6, which, except for the lack of prestress, was identical in every respect to MR-5. Since these specimens were both accurately centered it appears that the strength reduction of MR-5 was essentially due to the presence of initial residual stresses. Accordingly, if the initial flange prestress is added to the average direct stress at failure the ratio mentioned above becomes 0.93 which agrees very closely with the corresponding ratio obtained for MR-6.

Photographs of the three columns of this series after failure are shown in Fig. 43. The deflected shapes have been accentuated since the columns were loaded after they had failed until a large permanent set was obtained.

IV. CONCLUSIONS

Because of the limited series of tests performed, the following statements should not be generalized but should be regarded only as observations of pilot studies or exploratory tests.

1. The ultimate load and the ratio of ultimate stress to material yield point stress for each column are summarized in Table 1.
2. Failure of MW-1 and MW-2 occurred by lateral bending in a plane perpendicular to the web (the weak direction) without any significant rotation of the flanges. These specimens were only approximate scale models; their flanges possessed relatively greater torsional ridigity than the prototype flanges.
3. The difference in web thickness between model MW-1 and MW-2 had practically no effect on the ratio of maximum flange stress to material yield point stress even though the web of of MW-2 was so thin that it buckled elastically at a load of approximately 60 percent of the ultimate load. These results substantiate the analysis proposed in Progress Report 3 for columns of this open section which have flanges with a relatively large individual resistance against twisting with respect to the resistance of the entire column against lateral buckling.

4. A definite rotation of the flanges accompanied the lateral deflection failure which was noted for MW-3. The behavior of the 52-C series of large columns was fairly accurately reproduced in the test of this reasonably exact 1/6 scale model.

5. The ultimate strengths of all three models used in the investigation of lateral buckling and flange twist were not appreciably reduced by the freedom of the flanges to rotate.

6. The low ultimate load carried by stress-free model MR-4 was essentially due to an accidental eccentricity

7. The strength of prestressed model MR-5 which was fabricated with residual stresses of 7170 psi (compression) in the flanges and 10,350 psi (tension) in the web was approximately 20 percent less than the strength of the identical stress-free model MR-6 tested in the same manner.

8. The ratio of the total stress (initial prestress plus applied stress) in the flanges to the material yield point stress was equal to 0.93 for both the prestressed model MR-5 and the stress-free model MR-6. Although the number of tests are not sufficient to generalize, this agreement tends to substantiate the common assumption that yielding occurs in mild steel when the sum of the residual stresses and applied stresses reach the yield point stress of the material.

9. Techniques have been developed for the fabrication of thin-walled model columns. The results of the tests reported herein indicate that small-scale models are feasible for studying the behavior of large prototypes.

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TABLE I

SUMMARY OF RESULTS FOR MODELS OF MW AND MR SERIES

Model	Cross-Section Area, sq. in.	Ultimate Load, Pounds	Ultimate Stress, p. s. i.	Ultimate Stress / Yield Point	Remarks
MW-1	0.357	13,450	37,700	0.961	
MW-2	0.278	10,000	35,900	0.890	Based on gross area
			37,200*	0.923	Deducting proportion of load in web which buckled at 6000 lb.
MW-3	1.079	40,000	37,100	0.945	
MR-4	0.614	17,500	28,600	0.757	Non-axial condition of loading
MR-5	0.618	17,700	28,600	0.757	Neglecting pre-stress
			35,800*	0.932	Considering the pre-determined residual stress
MR-6	0.609	20,500	33,700	0.928	

* Ultimate flange stress

TABLE II

MECHANICAL PROPERTIES OF COUPONS OF MATERIALS USED FOR MW AND MR MODELS

Model	Coupon No.	Location	Compression Tests		Tension Tests				
			Yield Point p.s.i.	Modulus of Elasticity 10^6 p.s.i.	Yield Point p.s.i.	Modulus of Elasticity 10^6 p.s.i.	Ultimate Strength p.s.i.	Percentage Reduction of Area	Percentage Elongation in 2 inches
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
MW-1	1	Flange	-	-	37,700	30.4	67,000	56.6	25.7
	2	"	40,600	30.1	-	-	-	-	-
	3	"	-	-	37,900	33.0	67,700	55.0	32.5
	4	"	40,400	29.0	-	-	-	-	-
	5	"	-	-	40,000	30.3	67,200	52.4	31.5
	6	"	40,400	30.3	-	-	-	-	-
	7	Web	-	-	38,100	-	50,400	59.4	34.5
	8	"	-	-	39,000	29.4	50,000	58.2	-
	9	"	-	-	36,000	-	51,200	57.2	35.0
		3 in. section removed from model after failure	41,470	28.9	-	-	-	-	-
MW-2	1	Flange	-	-	38,600	29.1	76,000	43.7	28.0
	2	"	-	-	38,600	30.1	76,700	42.7	29.0
	3	"	-	-	39,400	27.8	77,600	37.1	30.0
	4	"	41,600	31.9	-	-	-	-	-
	5	"	42,600	32.5	-	-	-	-	-
	6	"	42,100	31.4	-	-	-	-	-
MW-3	1	Angle	-	-	46,100	30.0	53,800	54.4	25.2
	2	"	-	-	39,600	33.1	49,700	54.6	27.2
	3	"	-	-	45,500	28.3	52,000	63.1	25.2
	4	"	-	-	47,000	29.0	54,300	48.4	25.6
	5	"	-	-	46,100	28.8	53,000	46.8	27.5
	6	"	-	-	46,900	30.0	53,400	47.6	27.1

TABLE II (cont'd)

Model	Coupon No.	Location	Compression Tests		Tension Tests				
			Yield Point p.s.i.	Modulus of Elasticity 10^6 p.s.i.	Yield Point p.s.i.	Modulus of Elasticity 10^6 p.s.i.	Ultimate Strength p.s.i.	Percentage Reduction of Area	Percentage Elongation in 2 inches
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
MW-3	7	Angle	-	-	46,500	28.8	55,500	47.9	25.7
(cont'd)	8	"	-	-	-	-	53,700	47.1	26.8
	9	Flange plate	-	-	29,800	28.2	43,500	37.0	31.2
	10	"	-	-	24,900	19.4(?)	42,100	41.1	30.0
	B1	"	-	-	26,300	29.2	43,400	45.2	35.5
	B2	"	-	-	28,100	30.1	45,200	38.0	32.7
	B3	"	-	-	28,500	30.6	44,700	39.1	28.5
	11	Web plate	-	-	41,600	28.6	53,900	59.3	31.3
	12	" "	-	-	41,700	30.0	48,600	59.9	35.2
MR-4 }	1	All from same	-	-	-	-	54,200	65.6	36.5
MR-5 }	2	bar stock	-	-	36,800	29.7	52,900	65.6	36.0
	3		-	-	36,900	30.2	54,600	66.1	31.5
	4		-	-	38,800	30.2	54,500	65.1	36.0
	5		-	-	38,100	30.2	54,400	65.5	35.5
	6		-	-	38,100	29.7	56,800	63.9	37.0
MR-6	1	Web	-	-	36,300	30.1	52,800	61.2	37.0
	2	"	-	-	35,700	29.6	52,500	59.7	37.0
	3	Flange	-	-	37,200	31.8	53,500	59.9	35.5
	4	"	-	-	36,900	30.8	53,100	61.5	36.0
	5	"	-	-	35,300	29.9	52,100	62.3	39.0
	6	"	-	-	36,800	30.2	51,900	61.8	38.0

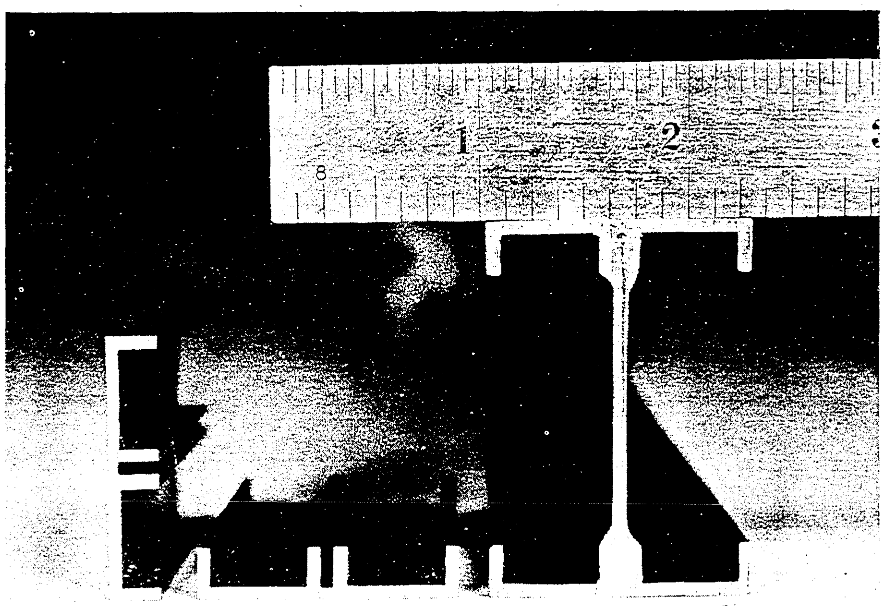


FIG. 1 CROSS-SECTIONAL VIEW OF MODEL MW-1

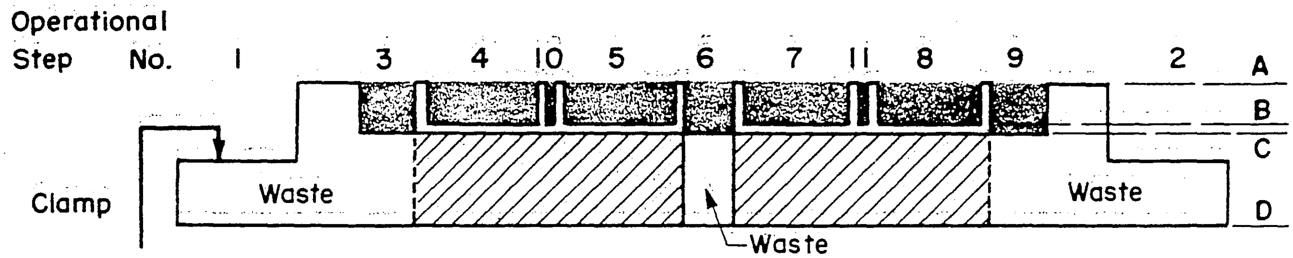


FIG. 2 DIAGRAM SHOWING MILLING PROCEDURES USED IN PREPARING FLANGES FOR MODELS MW-1 & MW-2

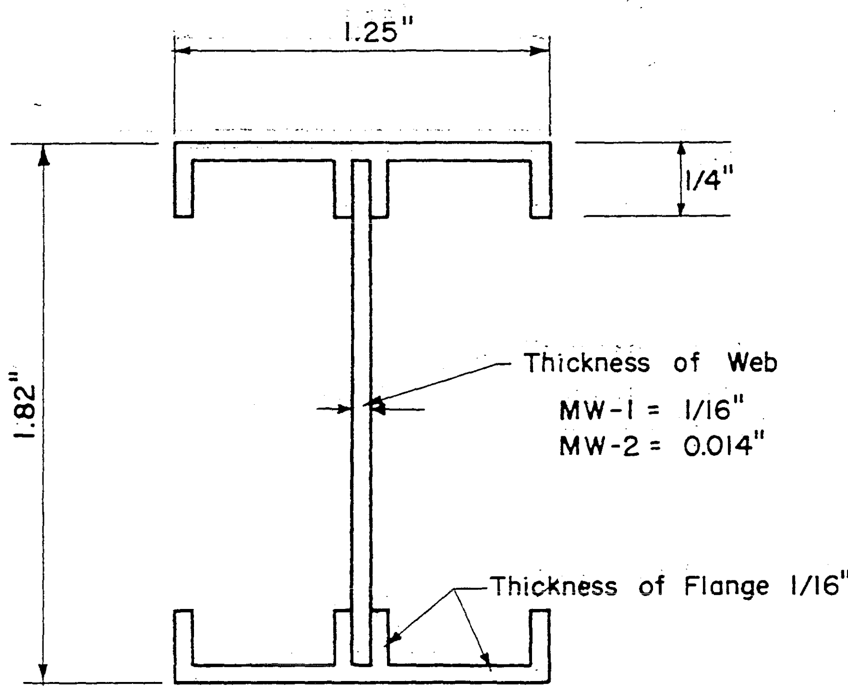


FIG. 3 CROSS-SECTION OF MODELS MW-1 AND MW-2

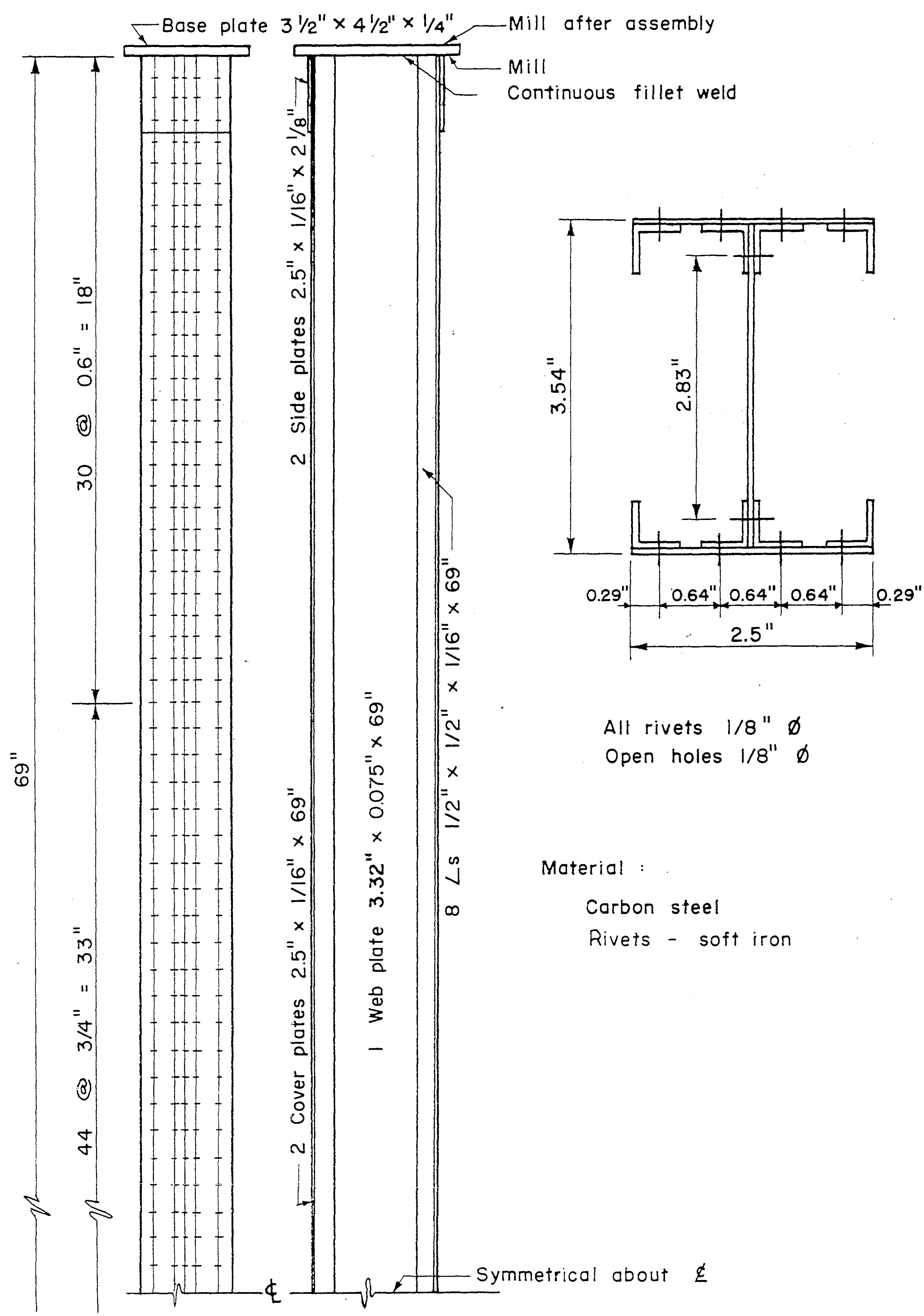


FIG. 4 DETAILS OF MODEL MW-3

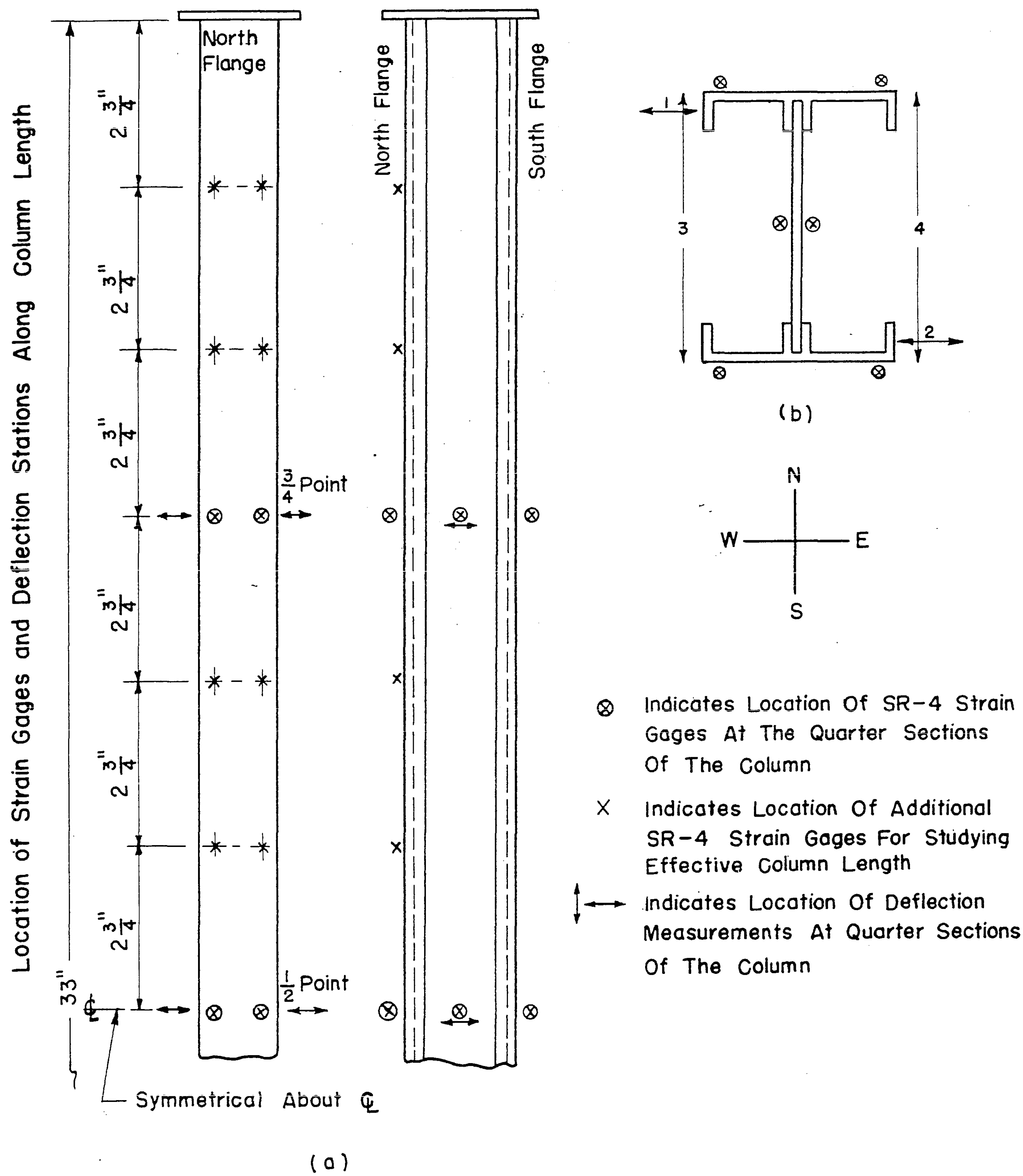


FIG. 5 LOCATION OF STRAIN GAGES AND DEFLECTION MEASUREMENTS FOR MODEL MW-1

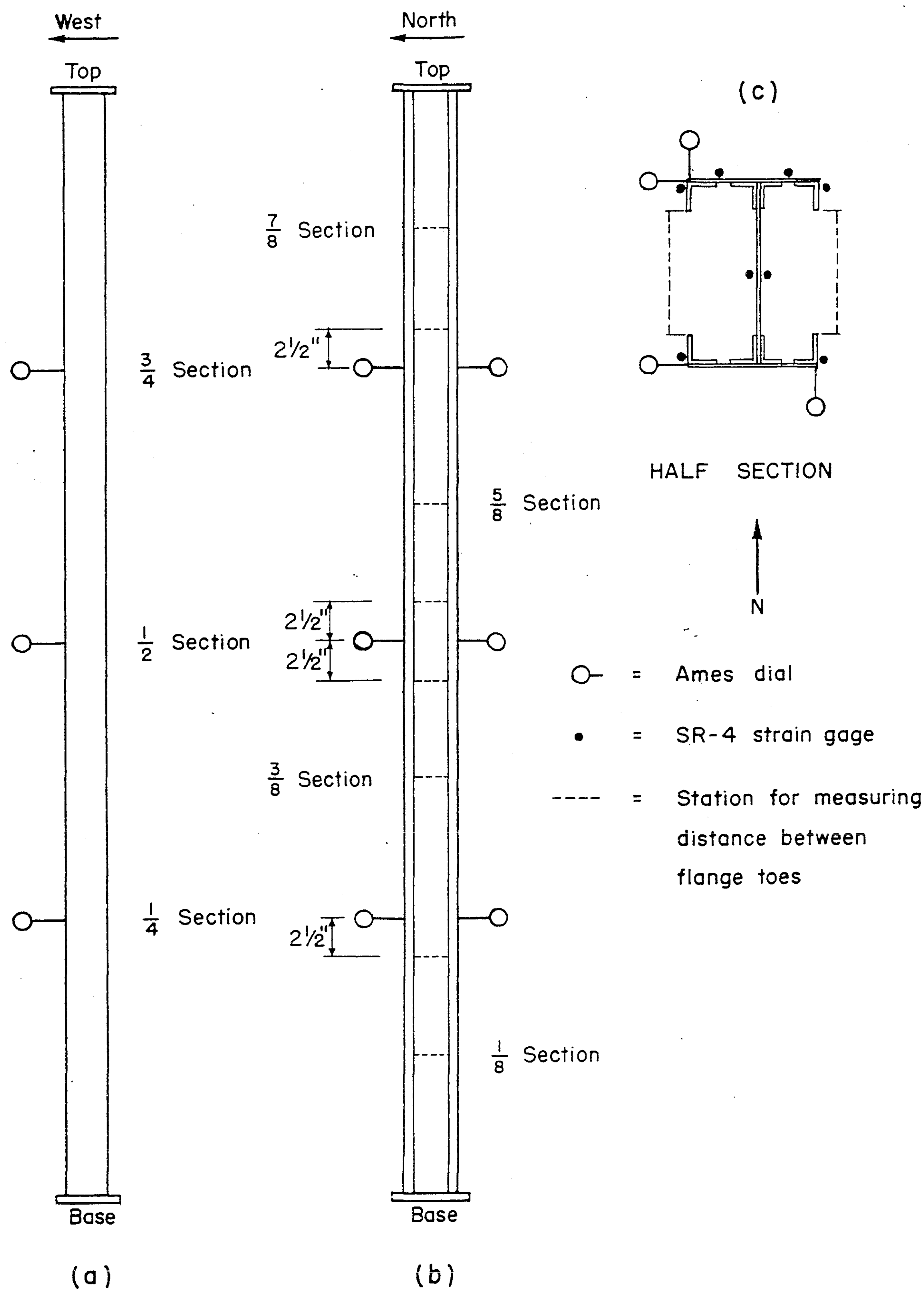
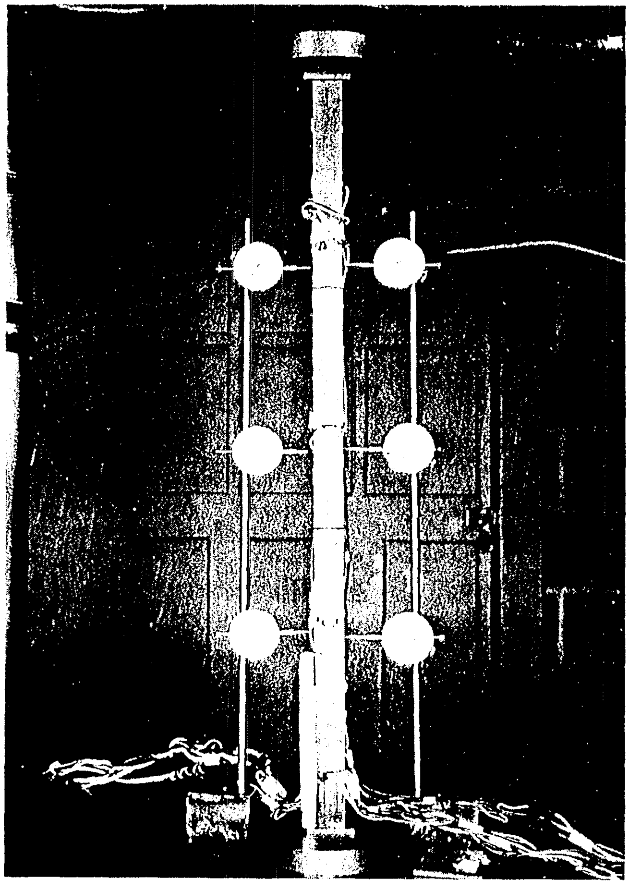
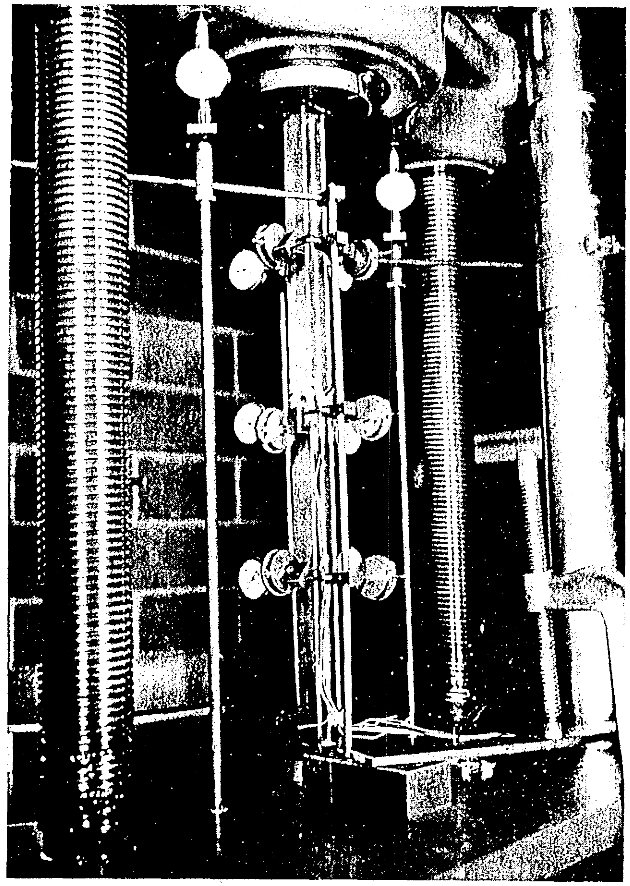


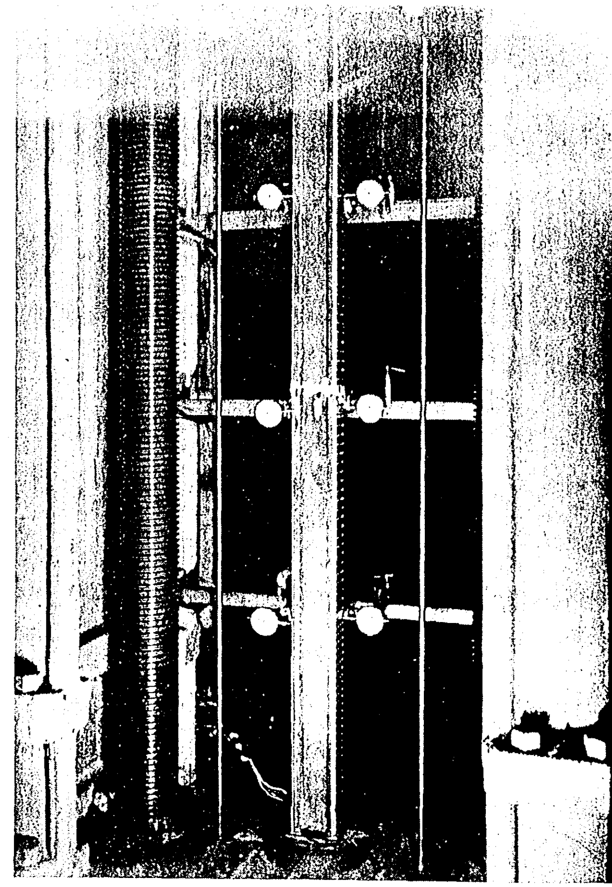
FIG. 6 LOCATION OF MEASURING DEVICES MODEL MW-3



(a) MODEL MW-1



(b) MODEL MW-2



(c) MODEL MW-3

FIG. 7 GENERAL VIEWS OF MW MODELS IN TESTING MACHINE

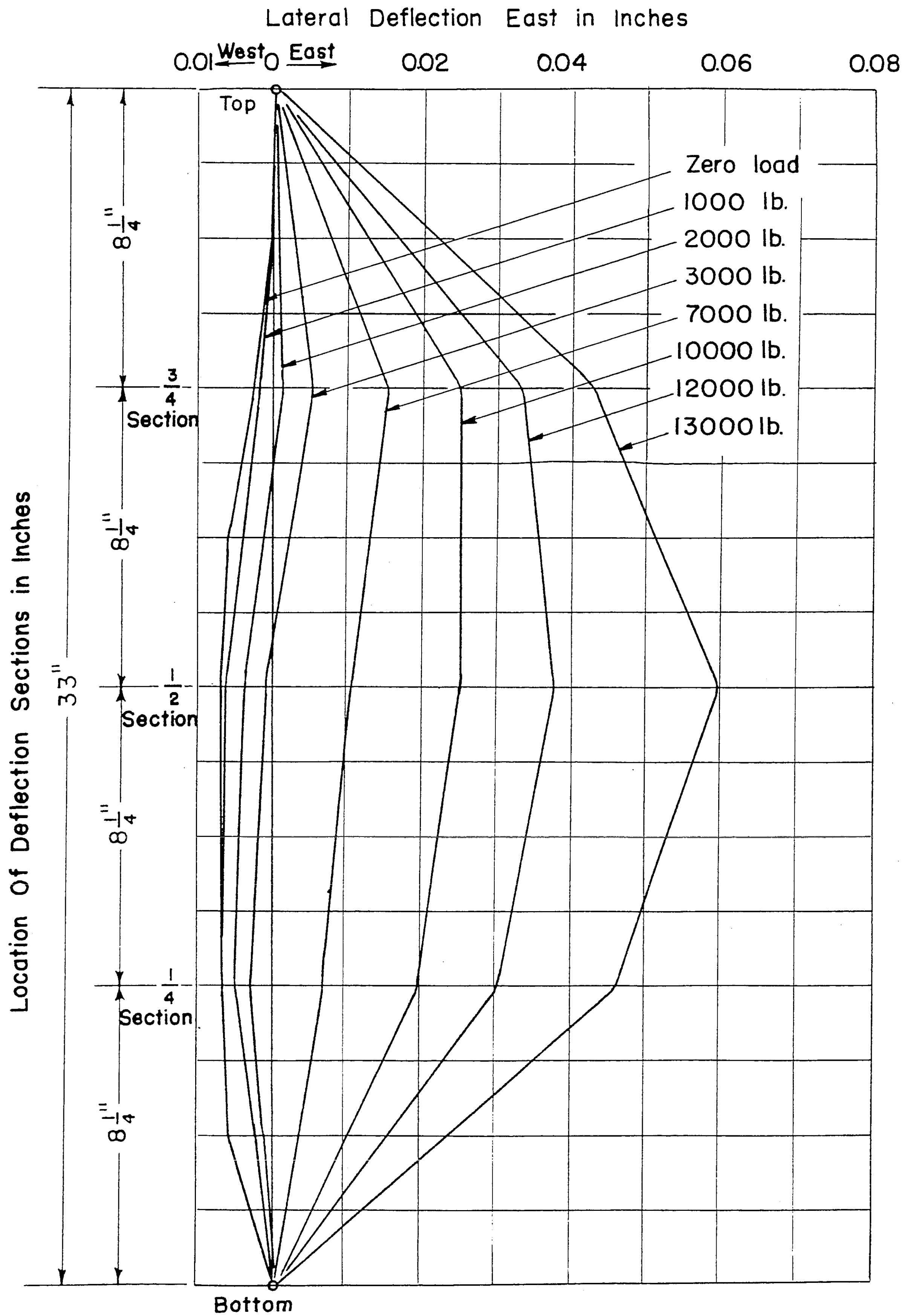


FIG. 8 LATERAL DEFLECTION — LOAD CURVES FOR SOUTH FLANGE COLUMN MW-1

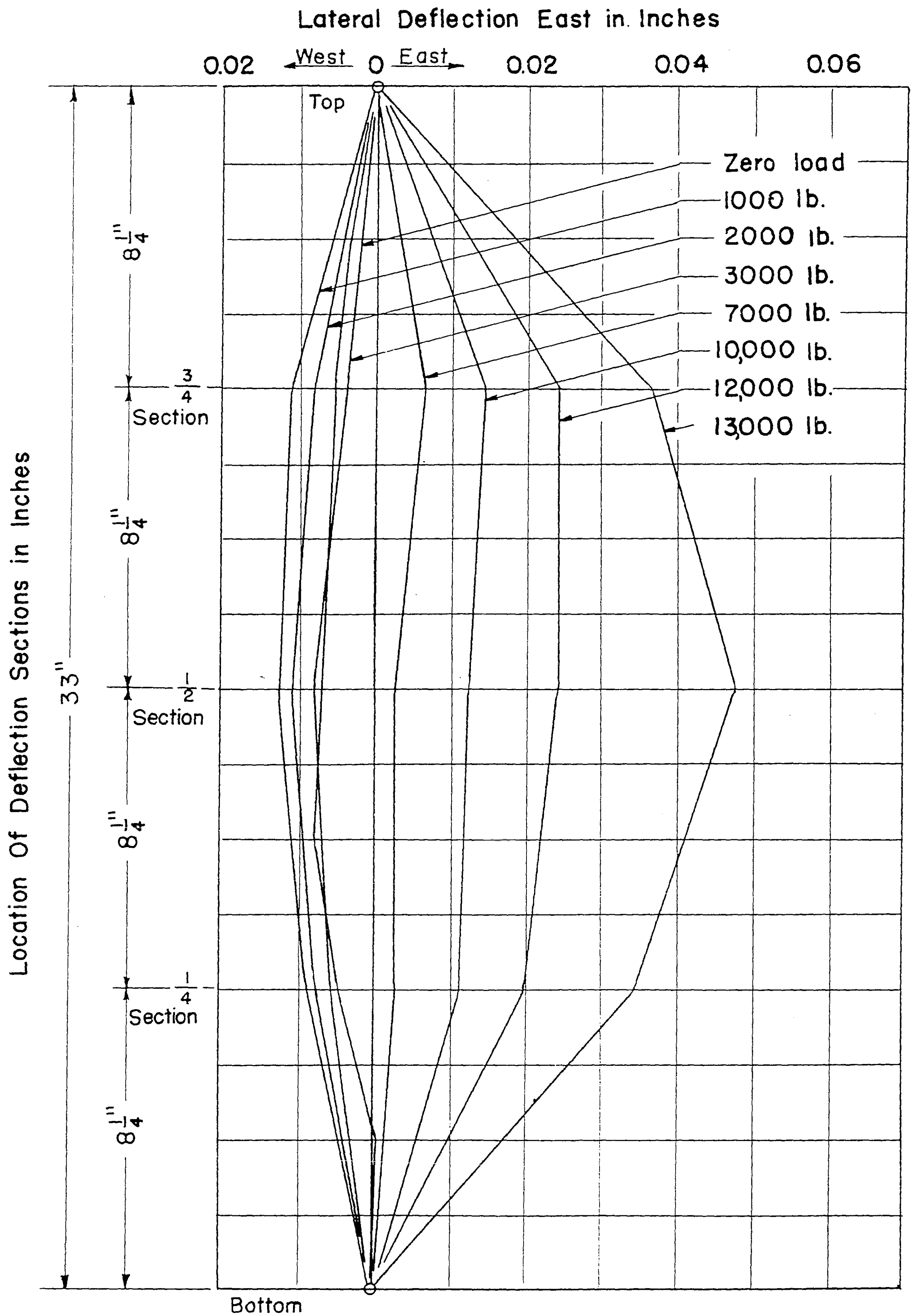


FIG. 9 LATERAL DEFLECTION — LOAD CURVES FOR NORTH FLANGE, COLUMN MW-1

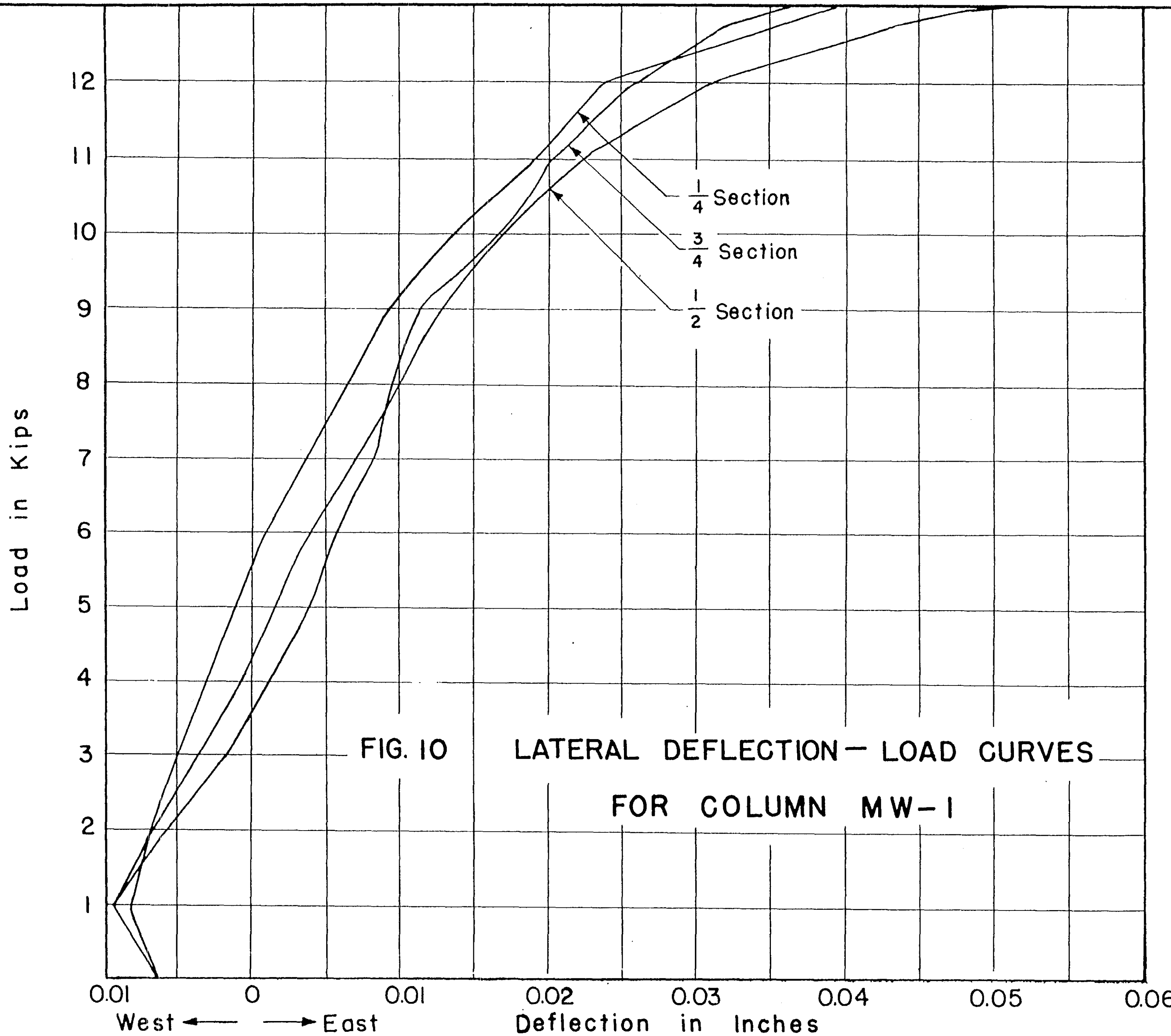


FIG. 10 LATERAL DEFLECTION — LOAD CURVES FOR COLUMN MW-1

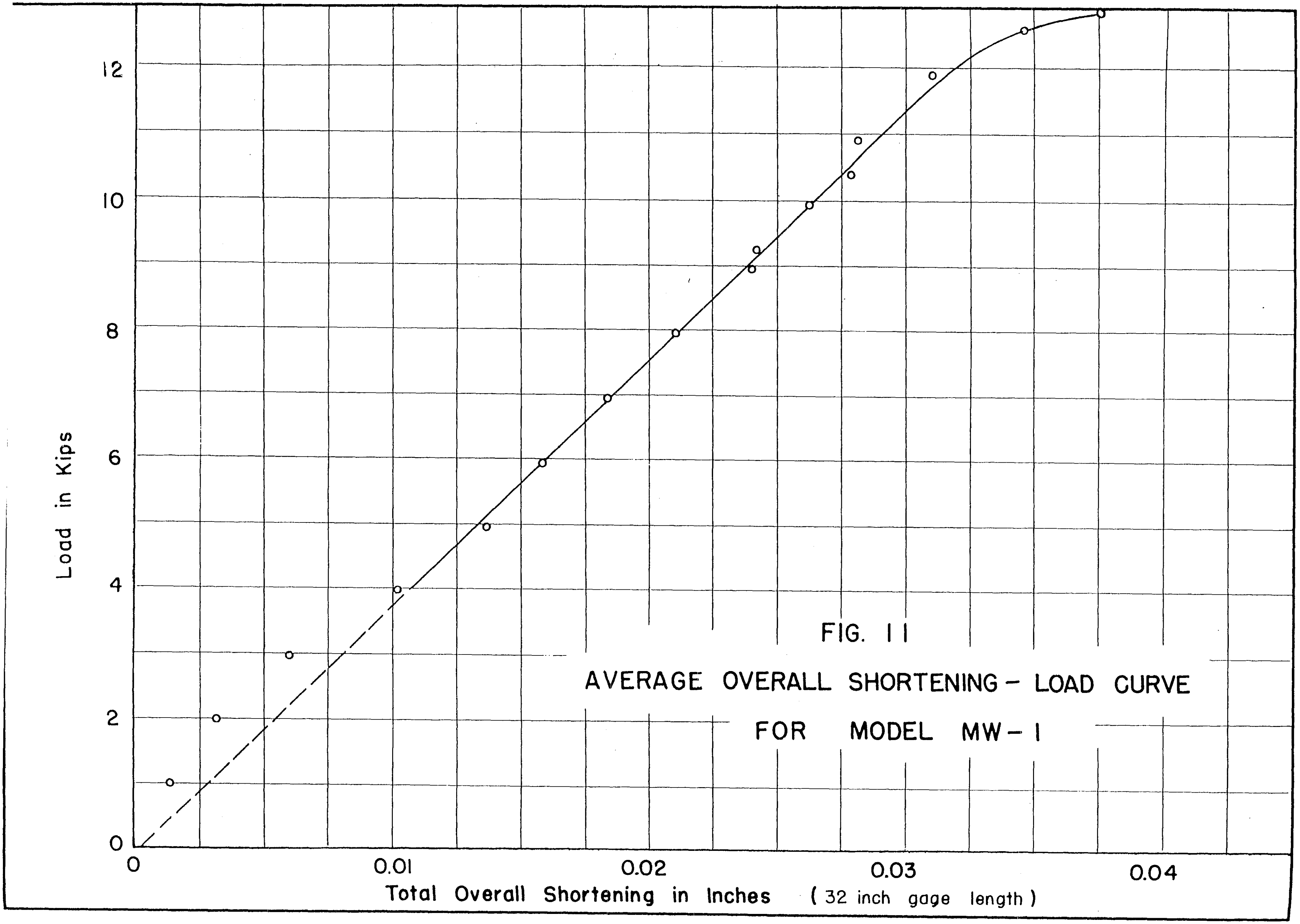


FIG. 11

AVERAGE OVERALL SHORTENING - LOAD CURVE FOR MODEL MW - 1

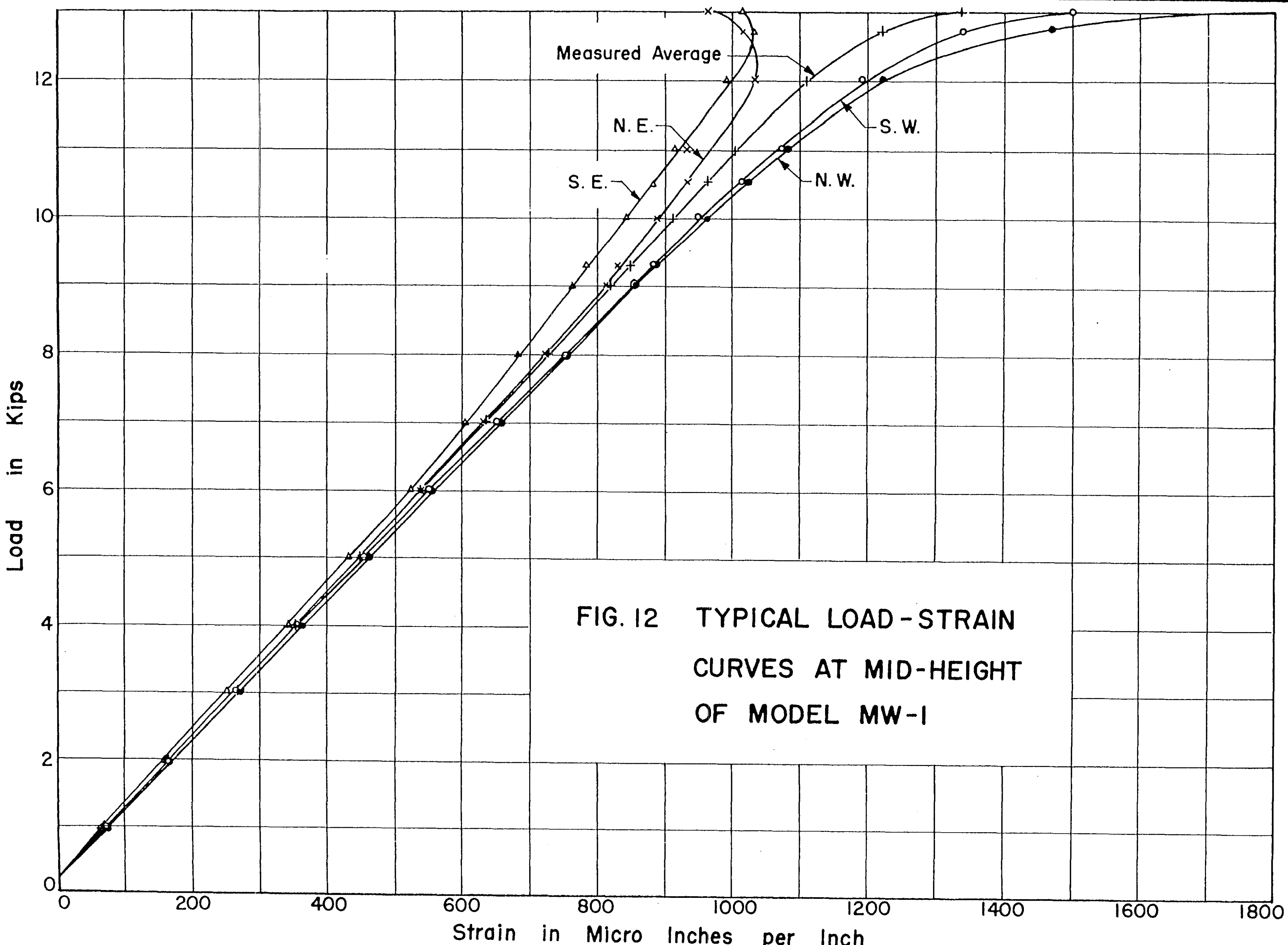


FIG. 12 TYPICAL LOAD-STRAIN CURVES AT MID-HEIGHT OF MODEL MW-1

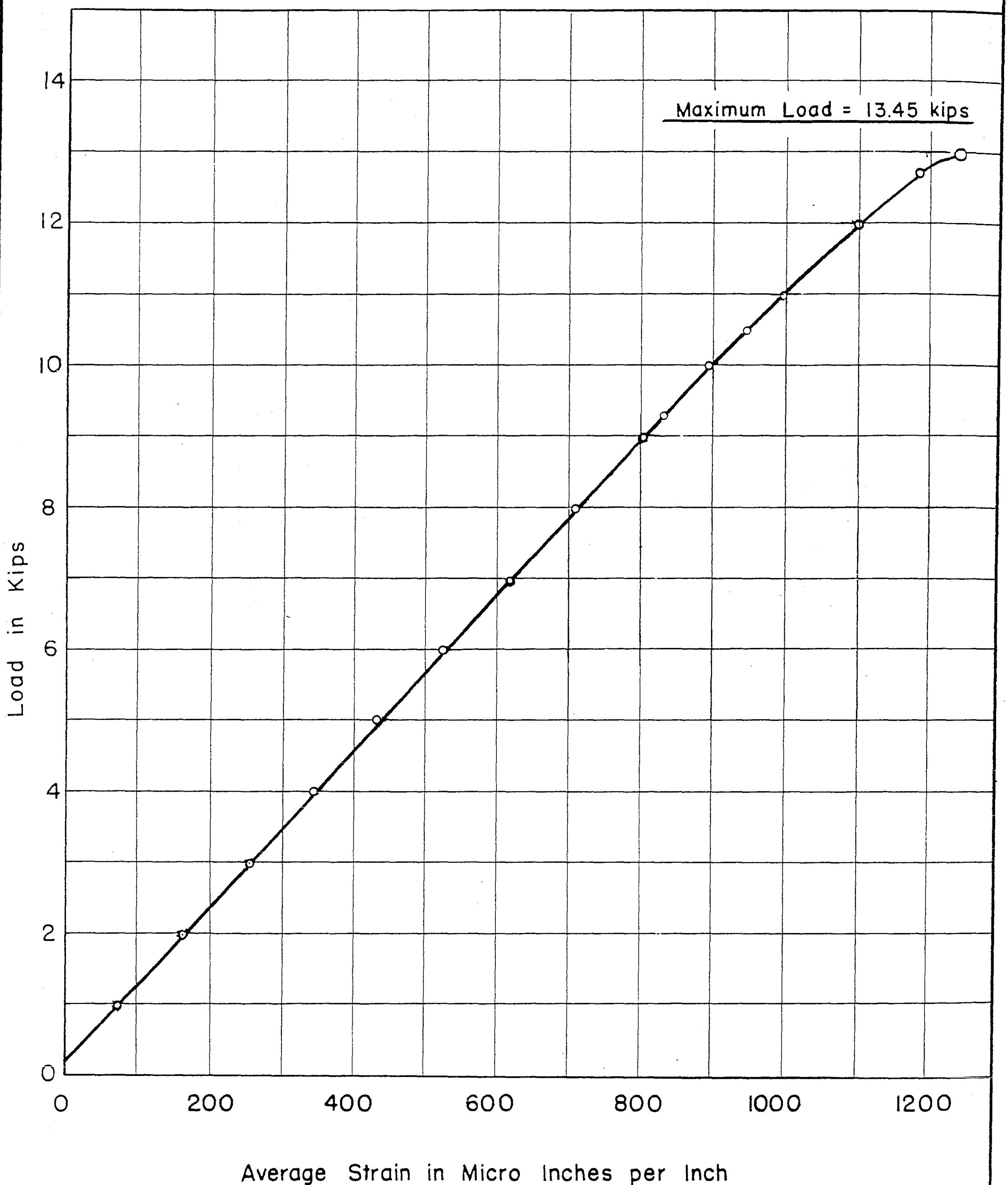


FIG. 13

AVERAGE LOAD- STRAIN DIAGRAM

MODEL MW-1

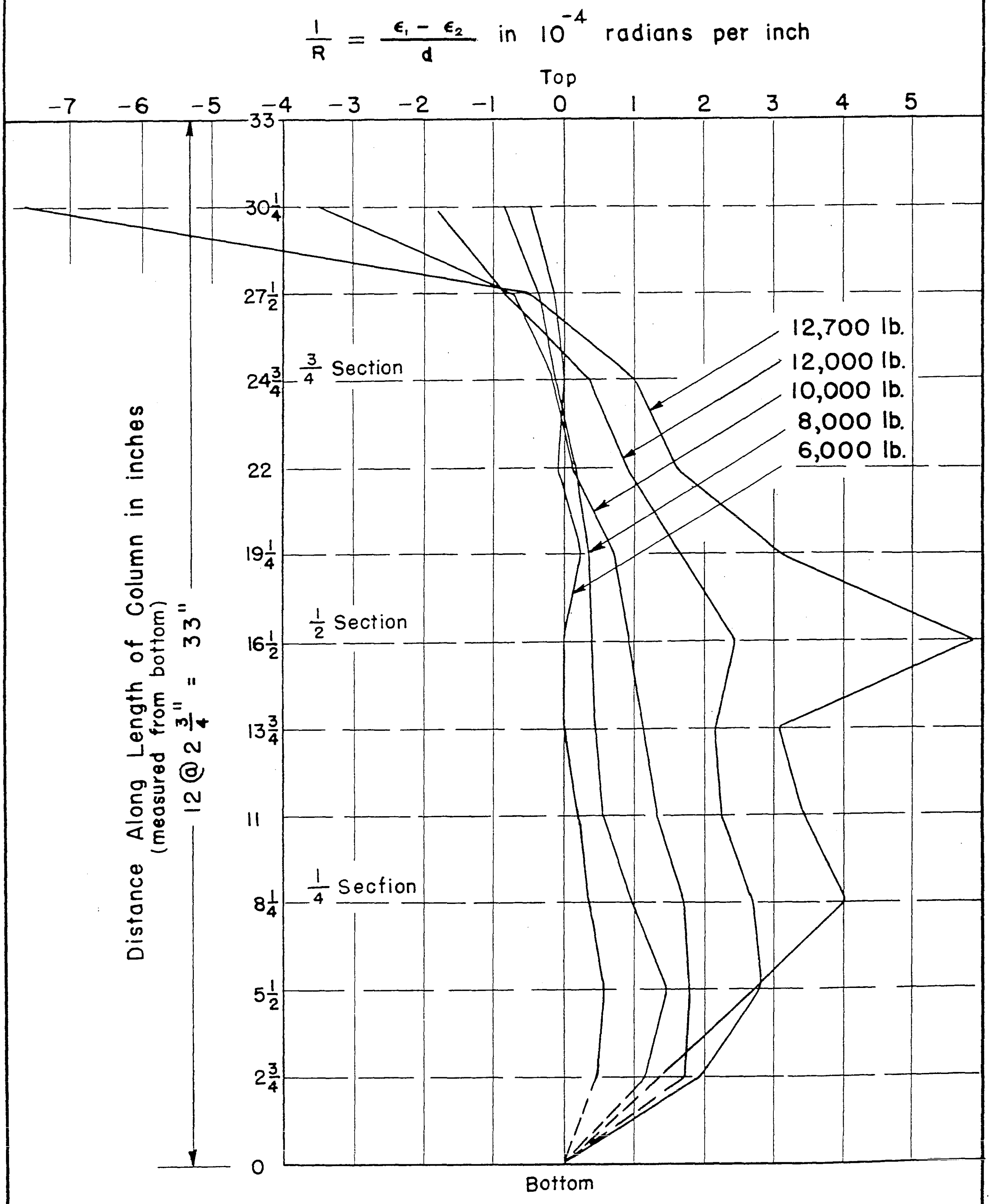


FIG. 14 CURVATURE PLOTS FOR COLUMN MW-1
SHOWING LOCATION OF POINTS OF INFLECTION

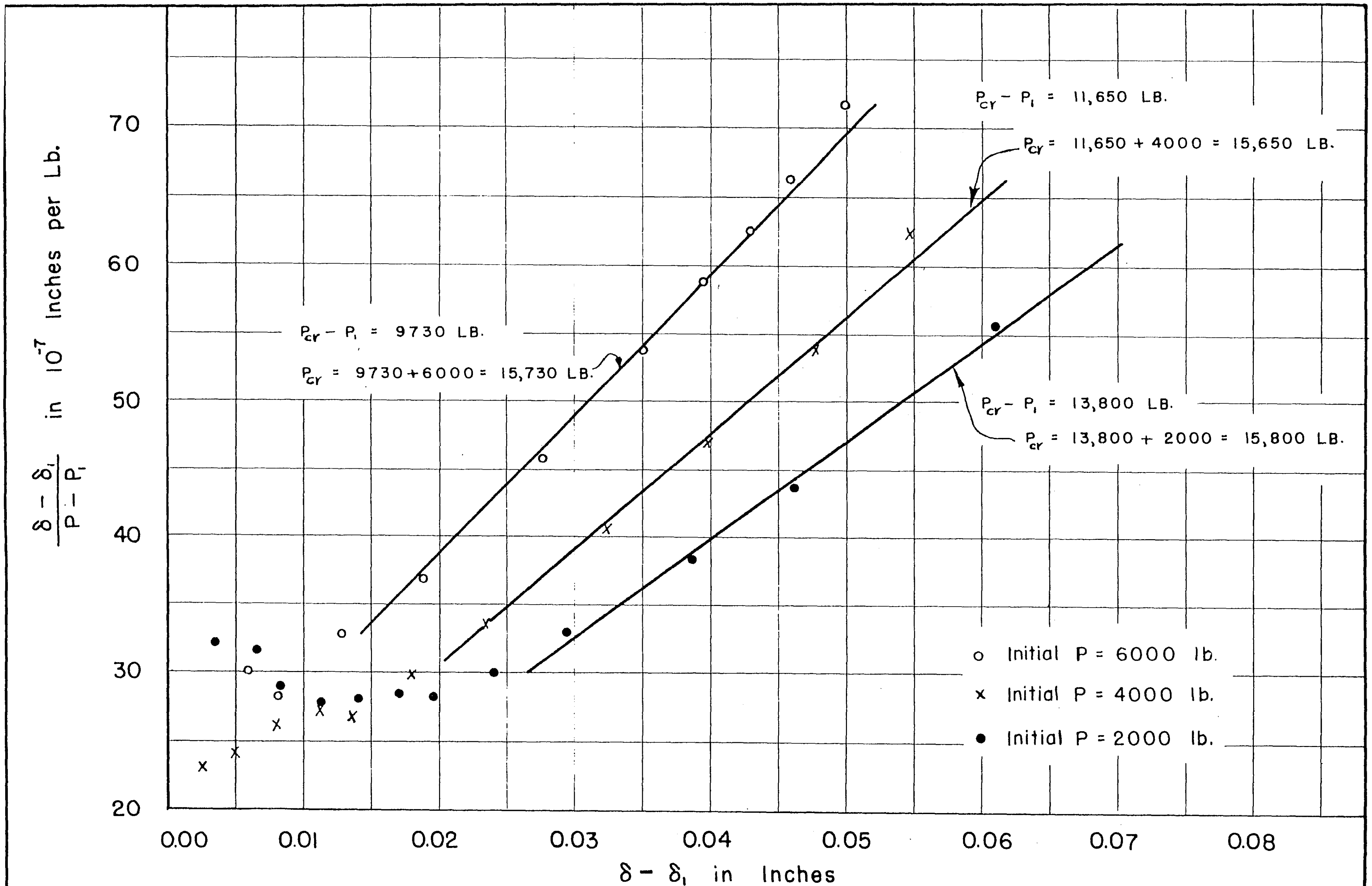


FIG. 15 LUNDQUIST PLOTS FOR ESTIMATING CRITICAL LOAD MODEL MW-1

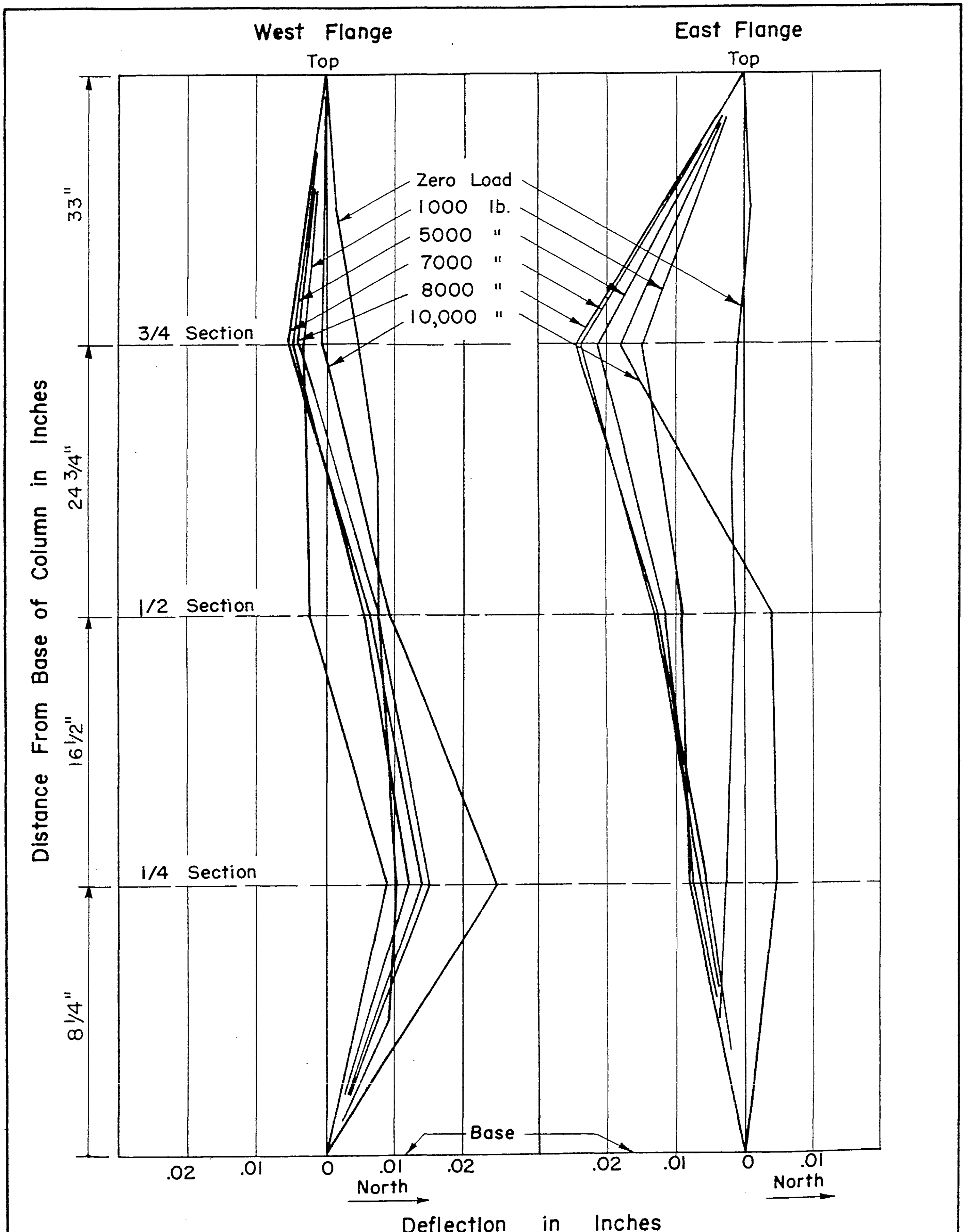


FIG. 16 LATERAL DEFLECTION OF FLANGES IN N-S DIRECTION AT VARIOUS LOADS, MODEL MW-2

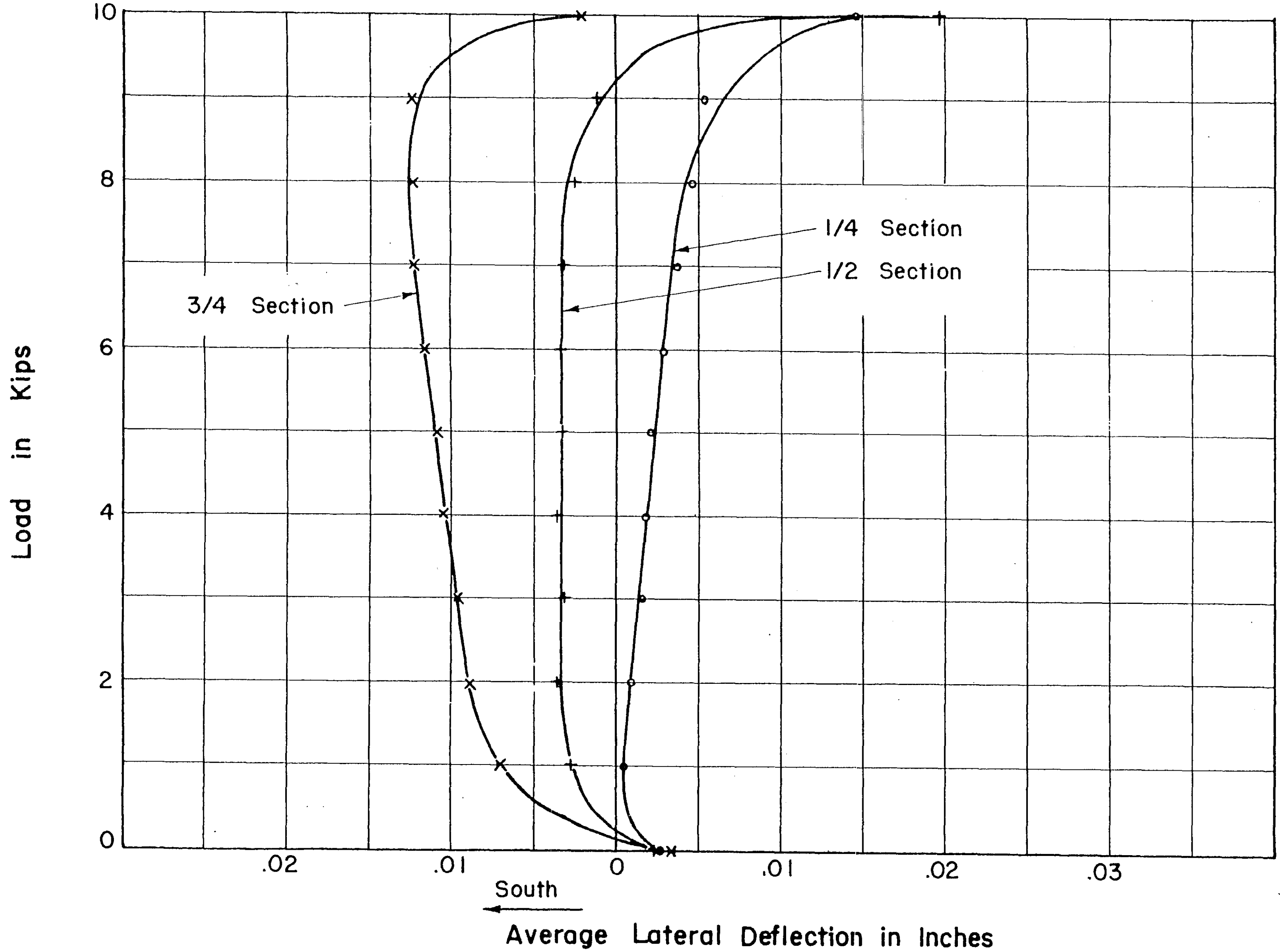


FIG. 17 AVERAGE LATERAL DEFLECTION-LOAD CURVES IN N-S DIRECTION FOR FLANGES OF MODEL MW-2

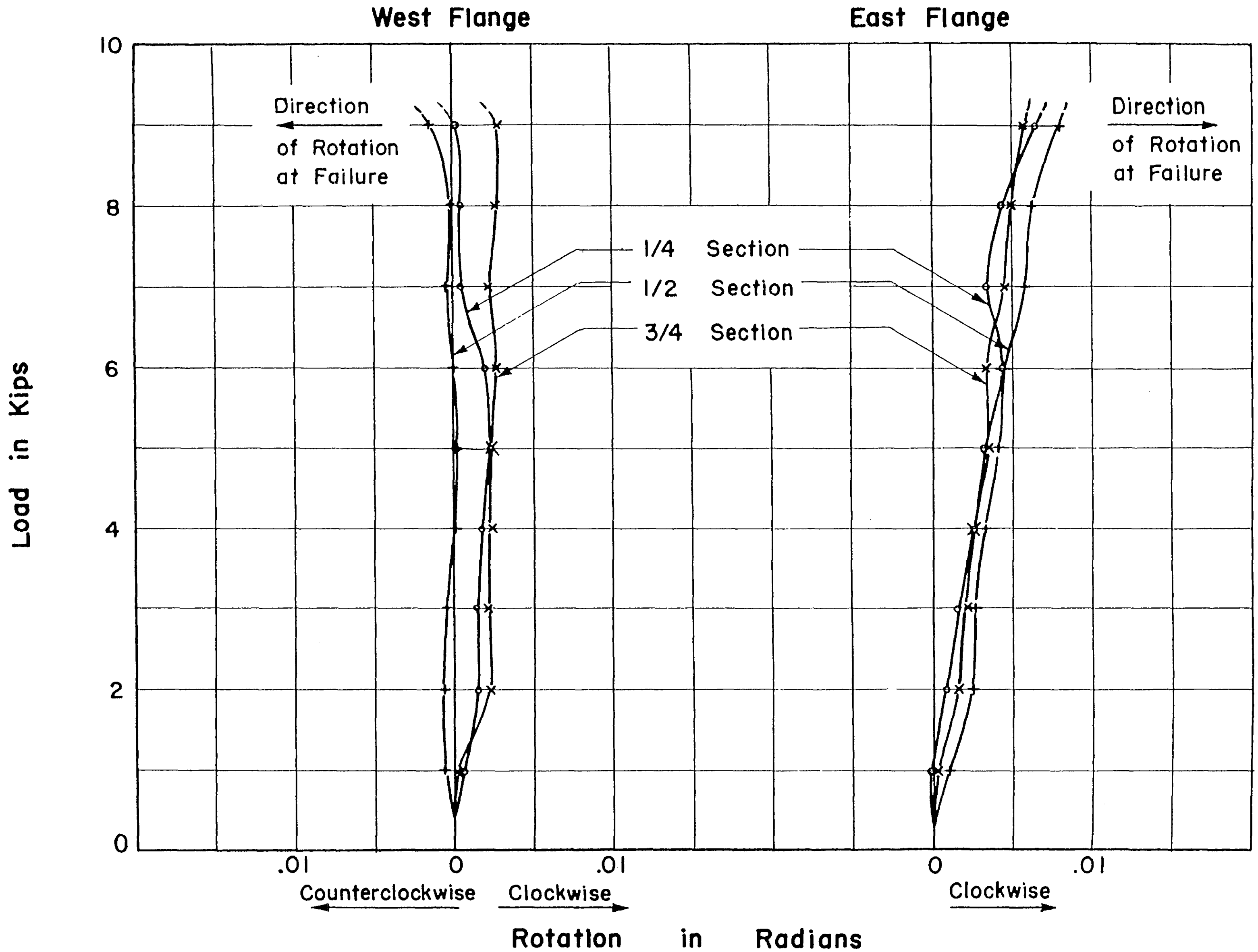


FIG. 18 FLANGE ROTATION - LOAD CURVES AT 1/4, 1/2 & 3/4 SECTIONS OF MODEL MW-2

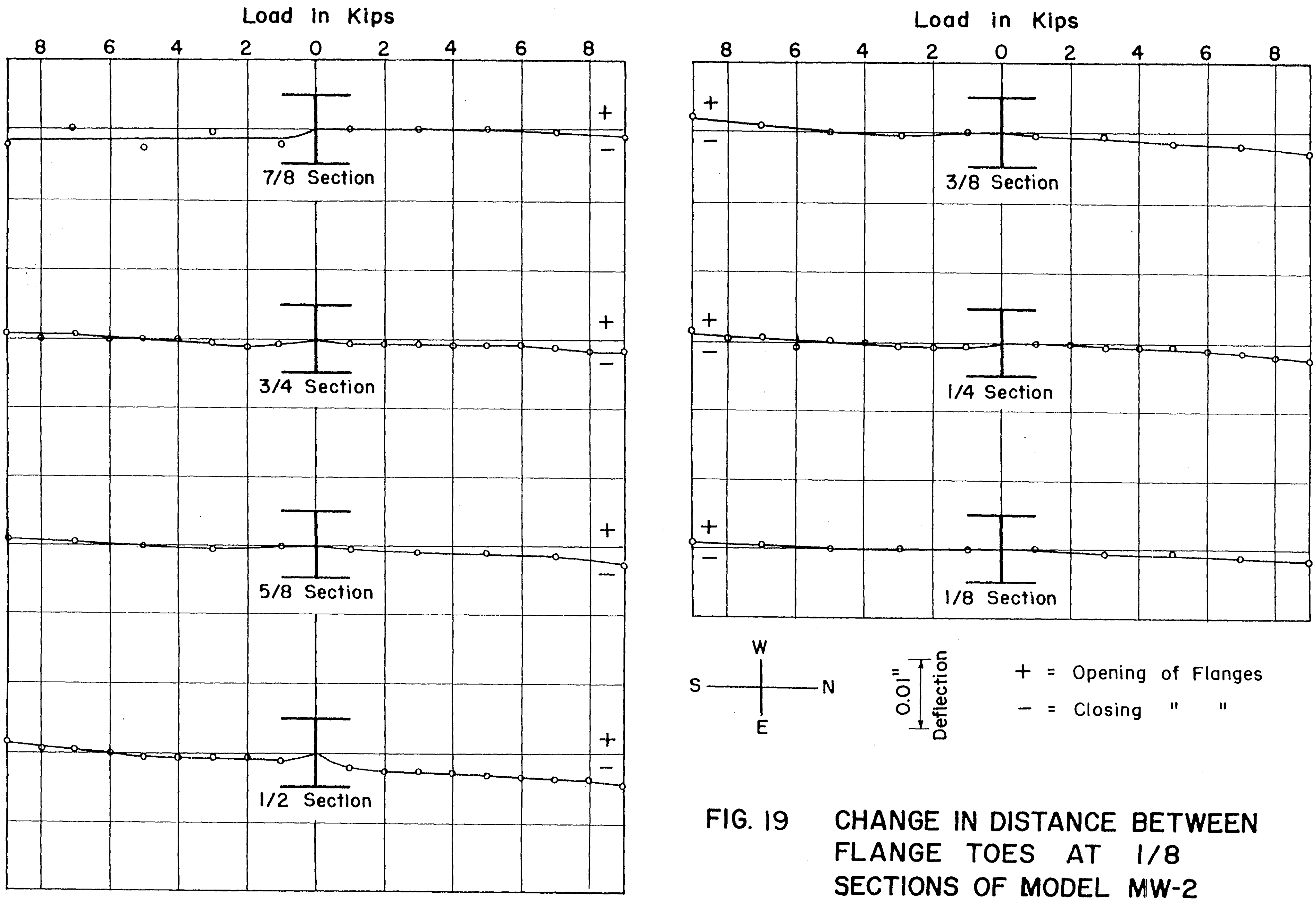


FIG. 19 CHANGE IN DISTANCE BETWEEN FLANGE TOES AT 1/8 SECTIONS OF MODEL MW-2

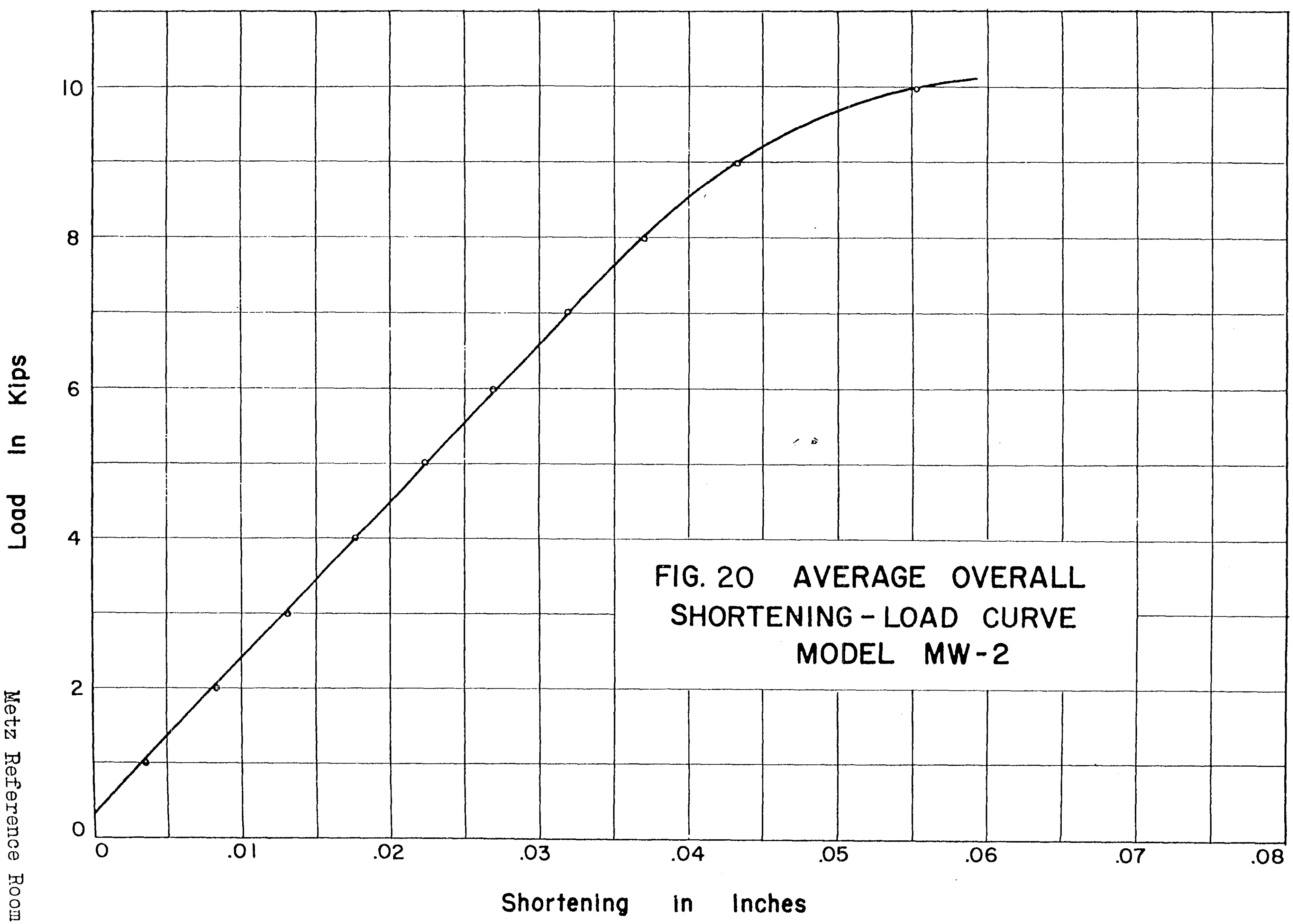


FIG. 20 AVERAGE OVERALL SHORTENING - LOAD CURVE MODEL MW-2

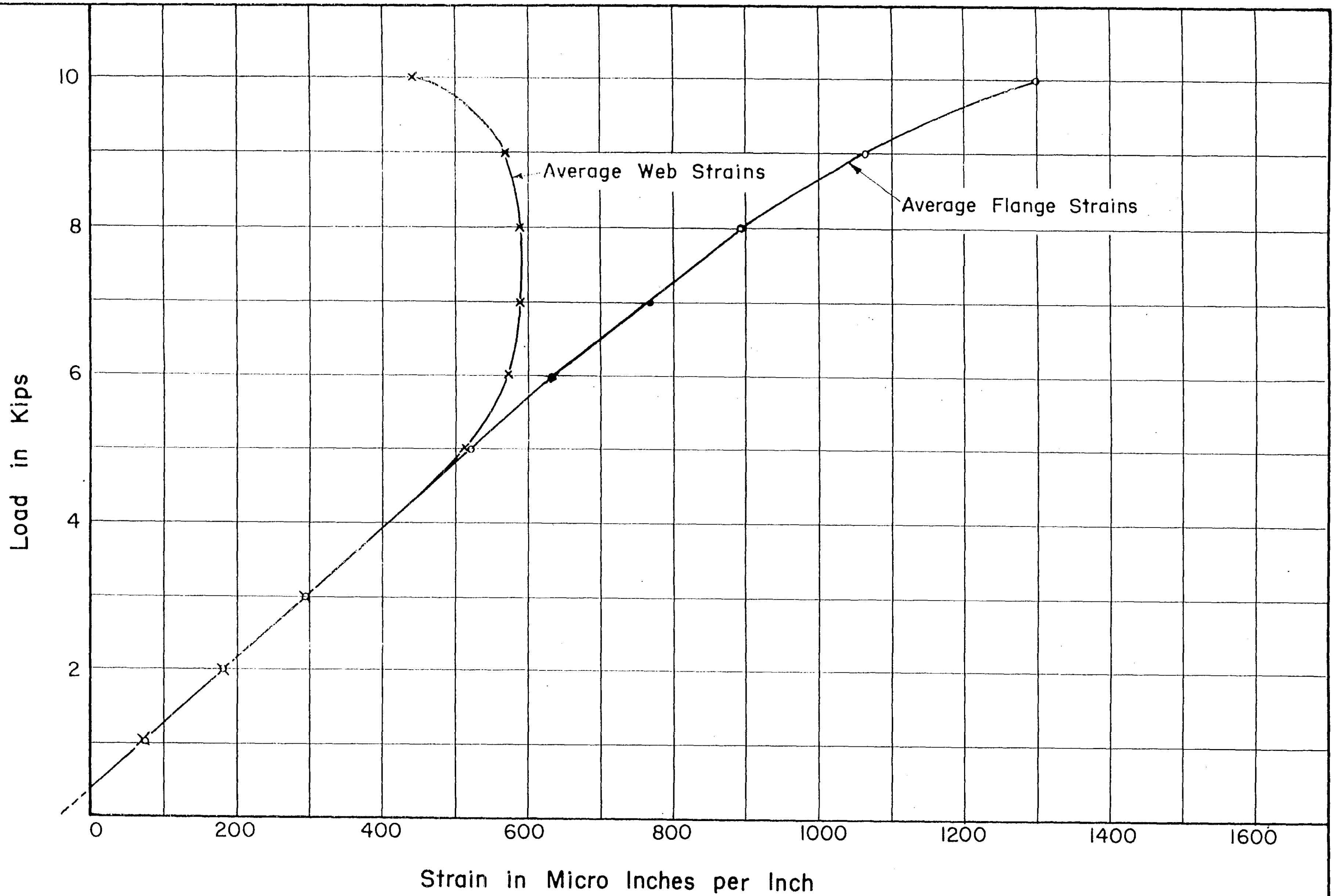


FIG. 21 AVERAGE STRAIN-LOAD CURVES FOR FLANGES AND WEB OF MODEL MW-2

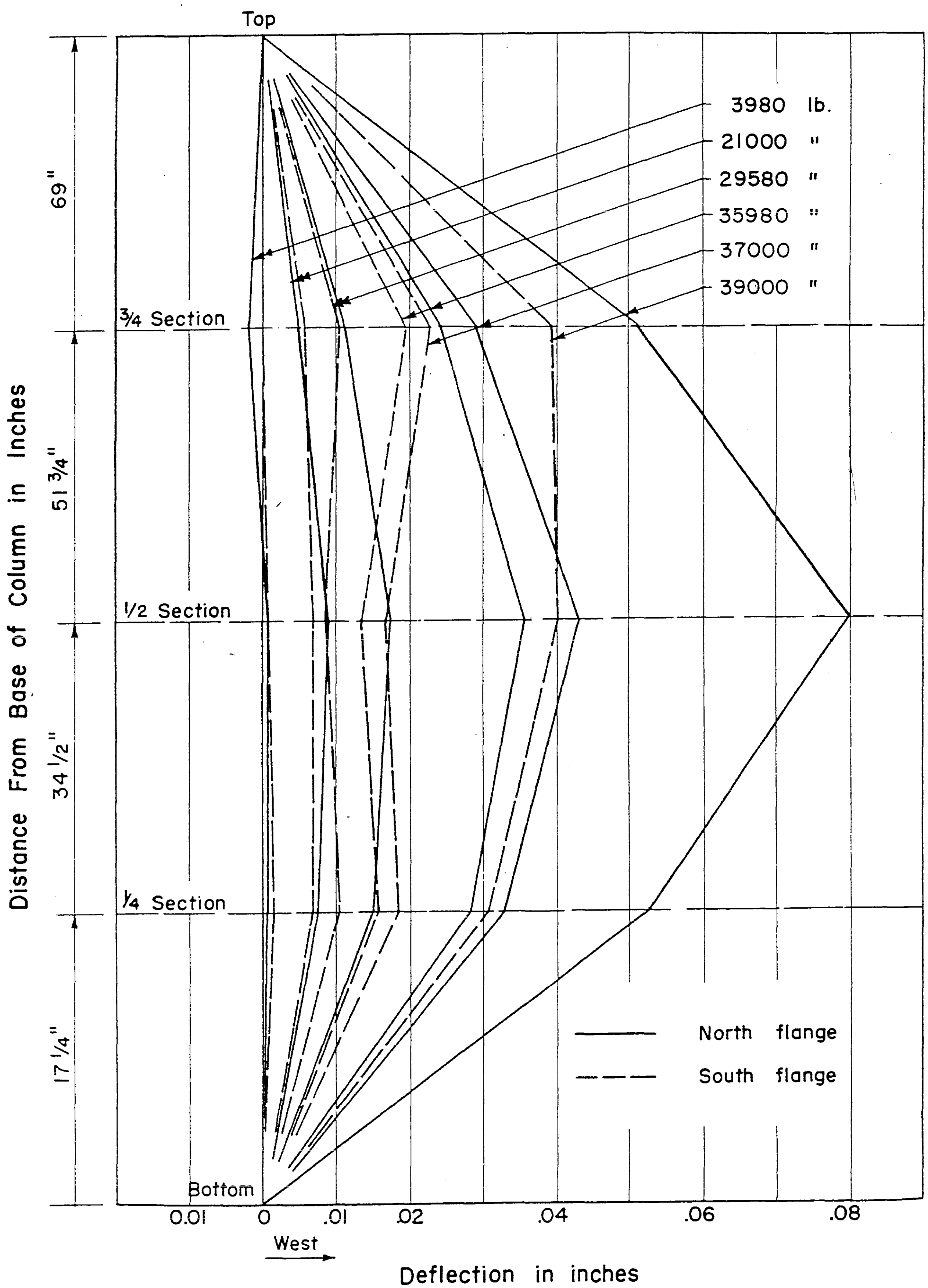


FIG. 22 LATERAL FLANGE DEFLECTION IN EAST-WEST DIRECTION AT VARIOUS LOADS. MODEL MW-3

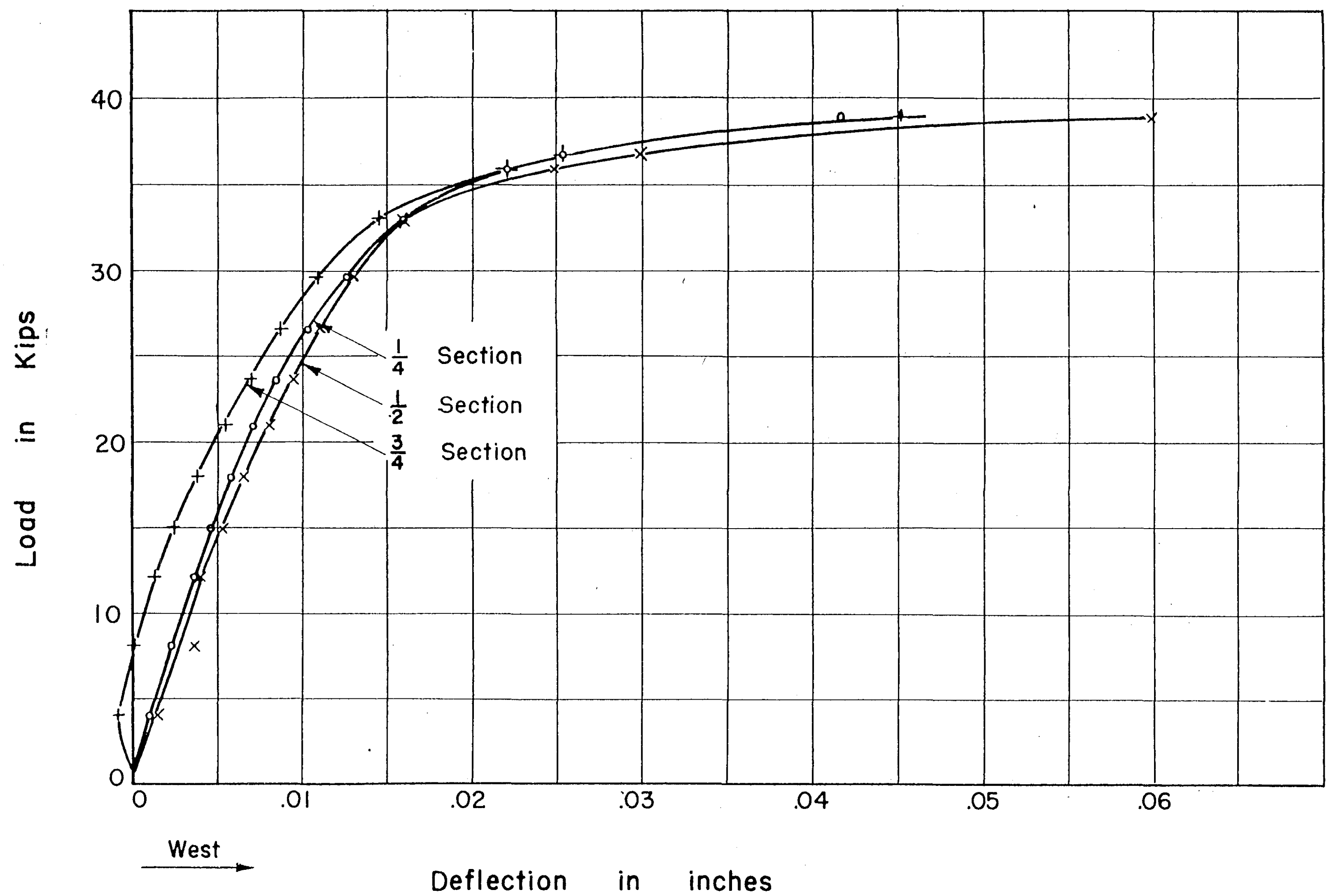


FIG. 23 AVERAGE LATERAL DEFLECTION-LOAD CURVES FOR FLANGES OF MODEL MW-3

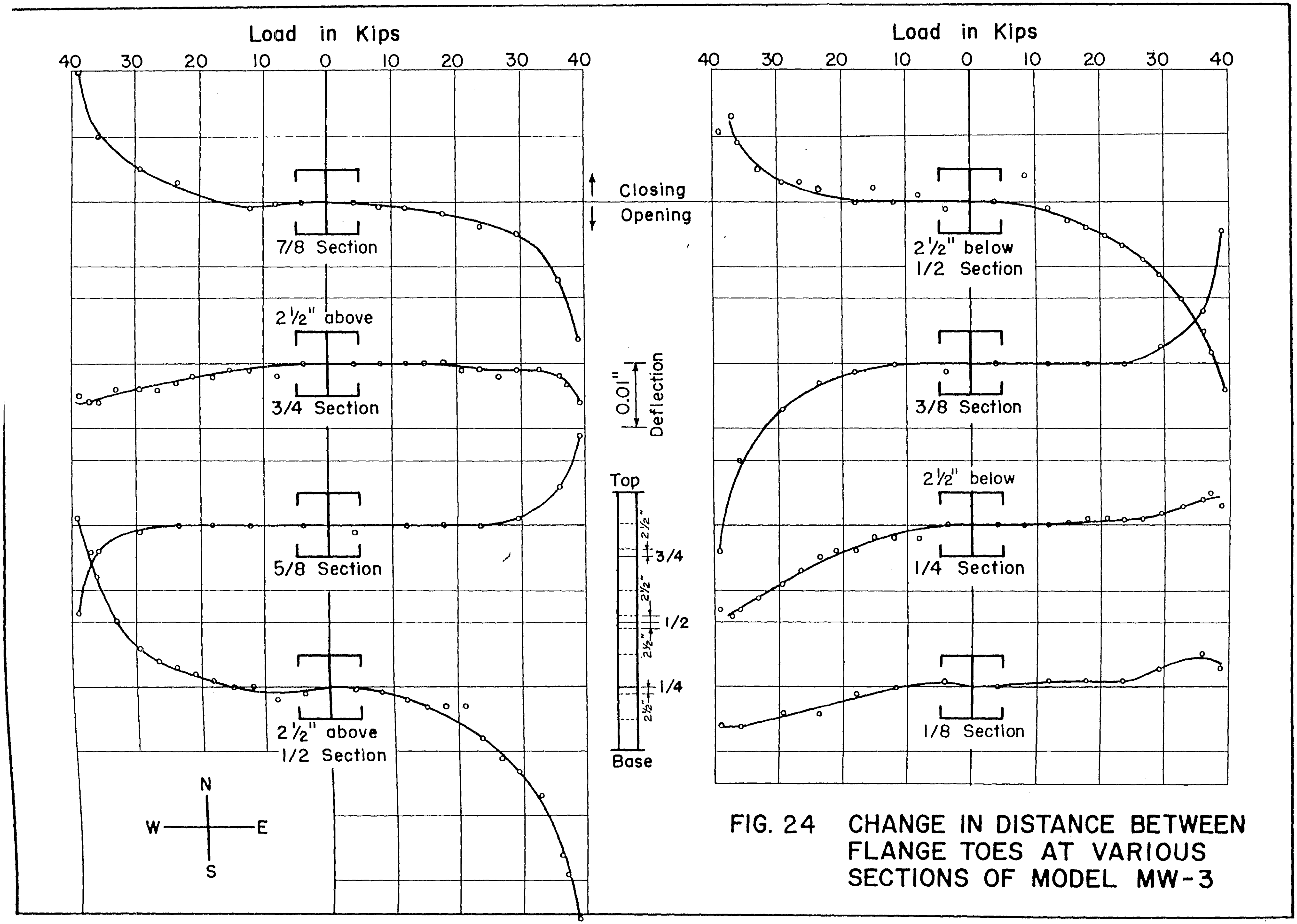


FIG. 24 CHANGE IN DISTANCE BETWEEN FLANGE TOES AT VARIOUS SECTIONS OF MODEL MW-3

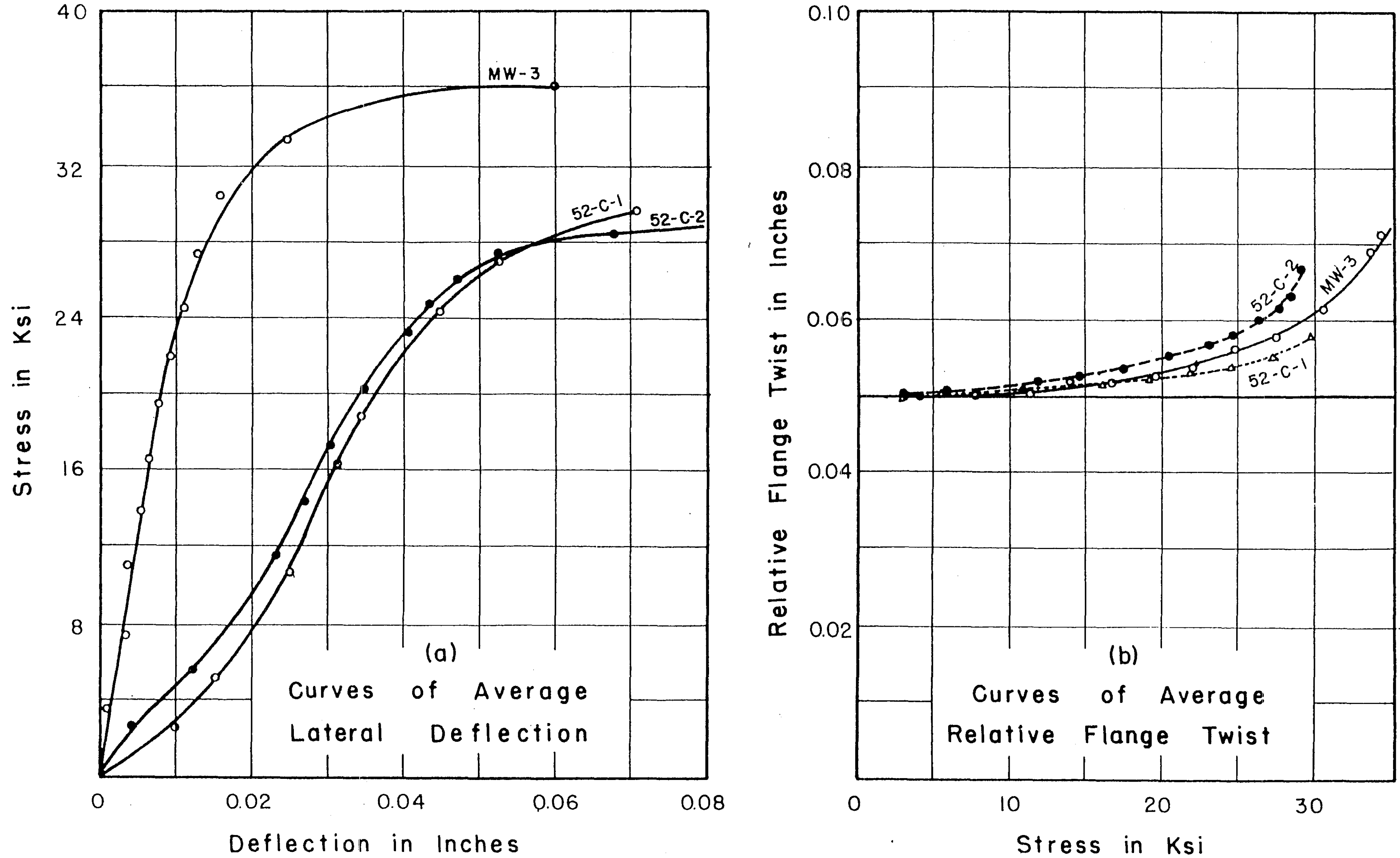


FIG. 25 BEHAVIOR OF MODEL MW-3 AND PROTOTYPE COLUMNS 52-C-1 AND 52-C-2 AT MID-SECTION

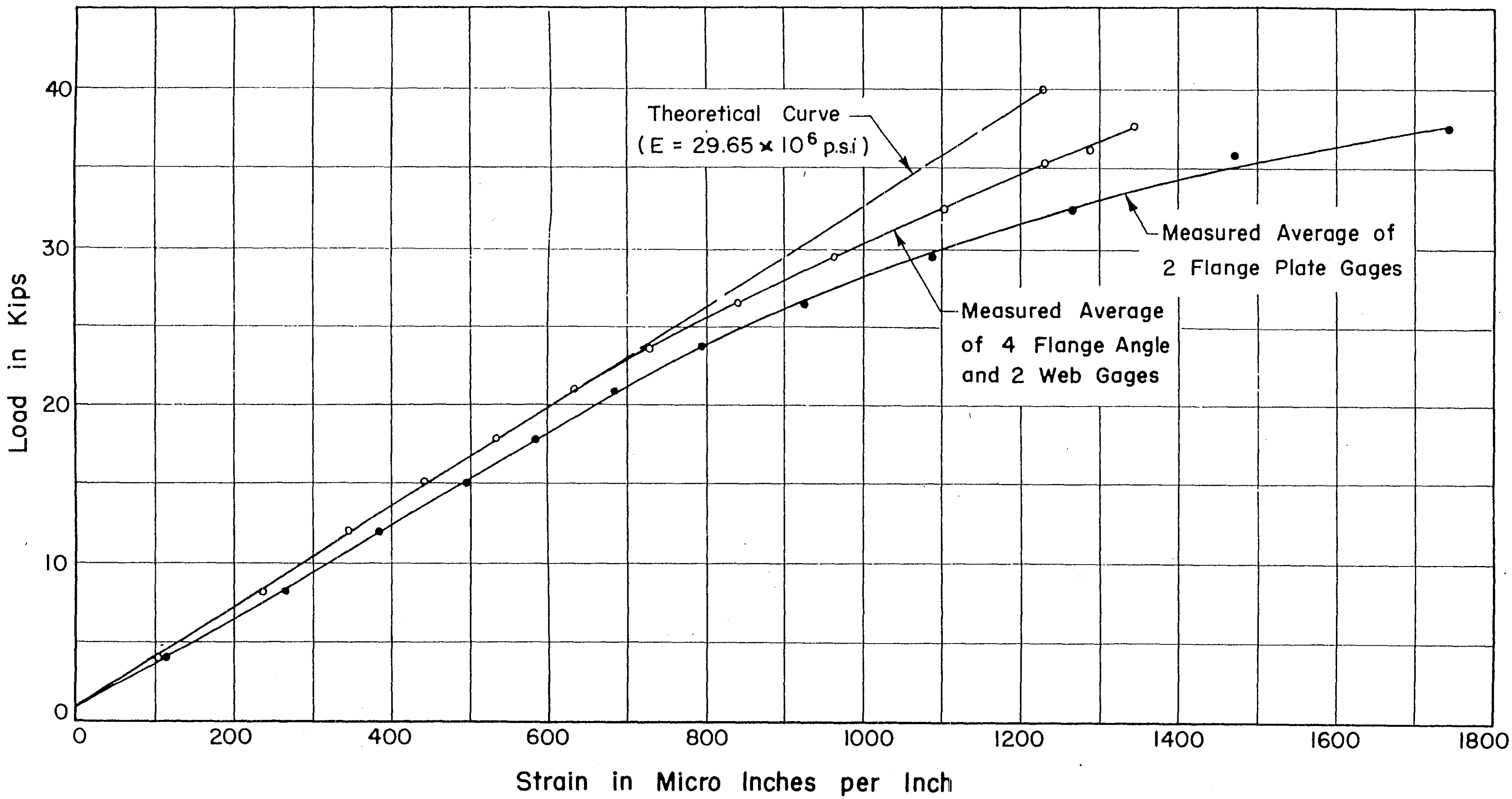


FIG. 26 AVERAGE STRAIN-LOAD CURVES AT MID-HEIGHT OF MODEL MW-3

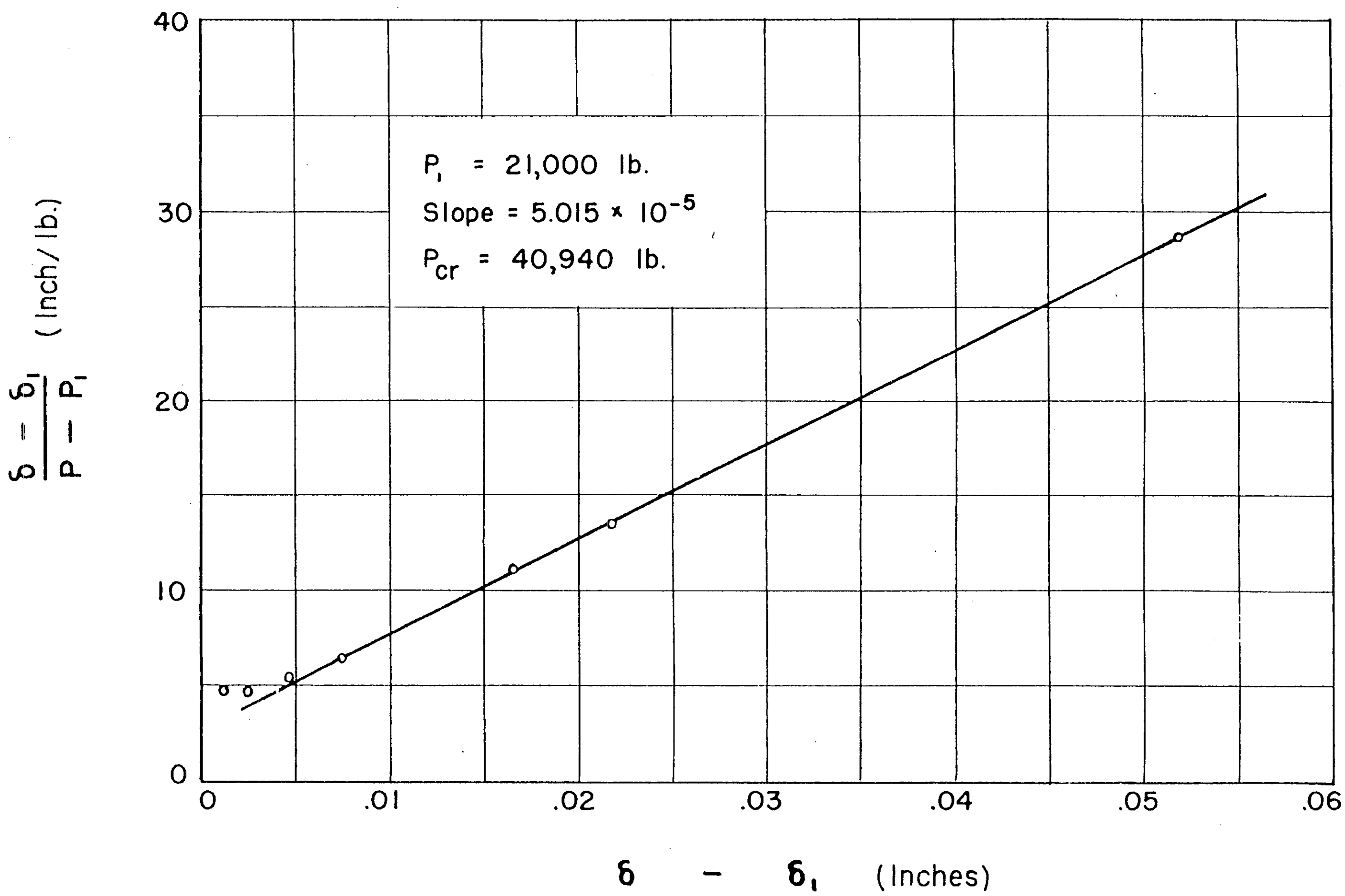
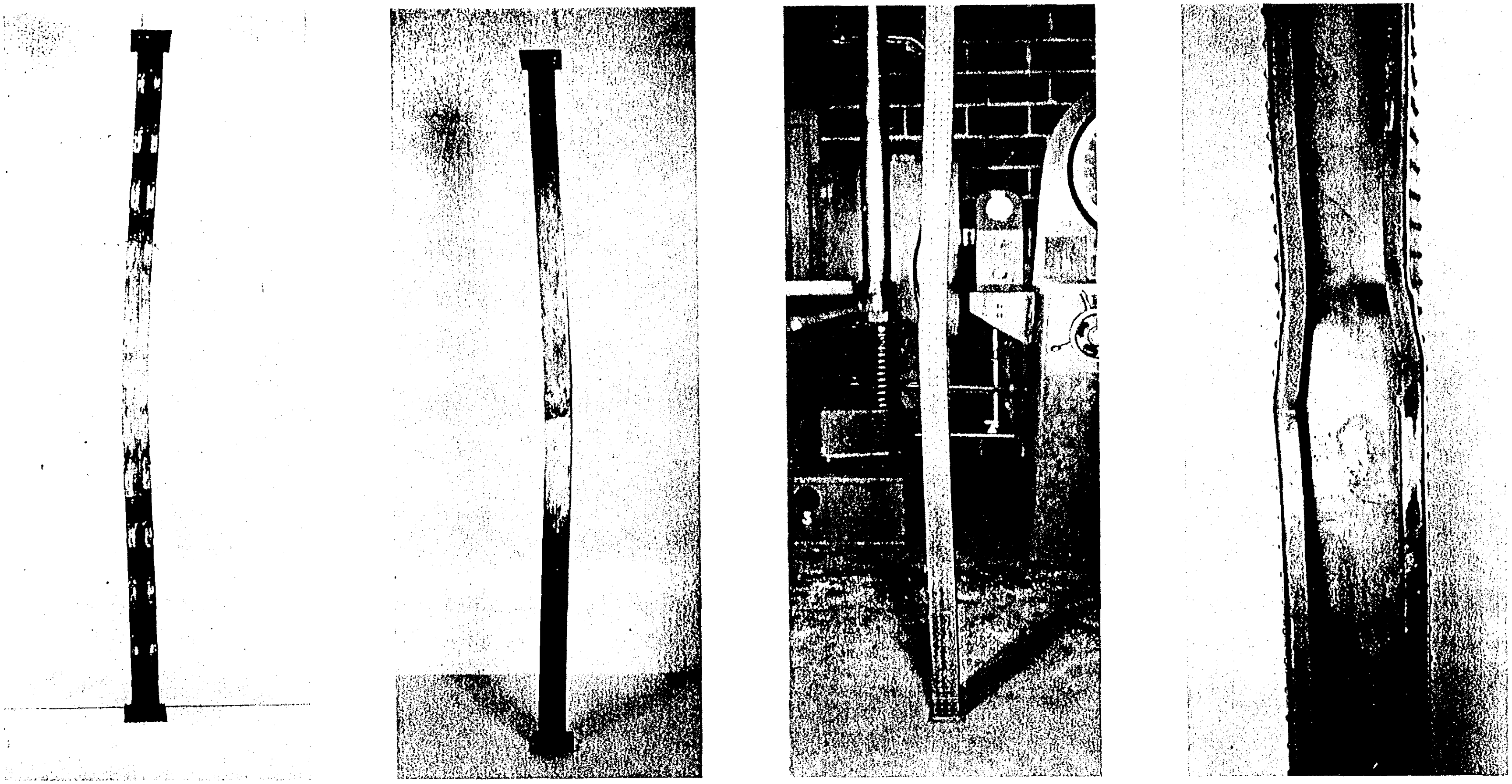
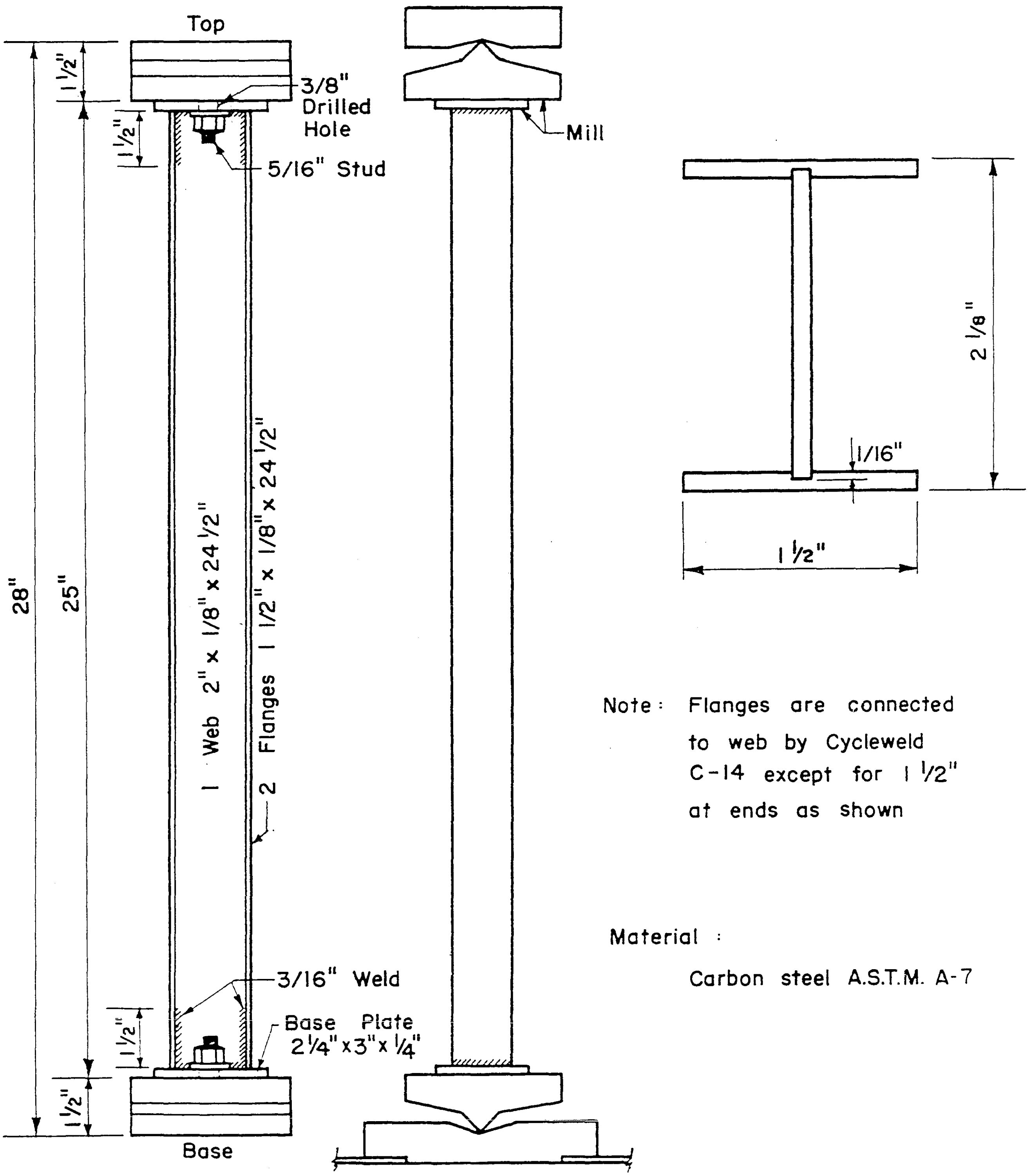


FIG. 27 ESTIMATE OF ULTIMATE LOAD FOR MODEL MW-3
BY LUNDQUIST PROCEDURE



(a) MODEL MW-1 (b) MODEL MW-2 (c) MODEL MW-3 (d) MW-3 AT MID-SECTION

FIG. 28 MW MODELS AFTER FAILURE



Note: Flanges are connected to web by Cycleweld C-14 except for 1 1/2" at ends as shown

Material :

Carbon steel A.S.T.M. A-7

FIG. 29 DETAILS OF MODELS MR-4, MR-5 & MR-6

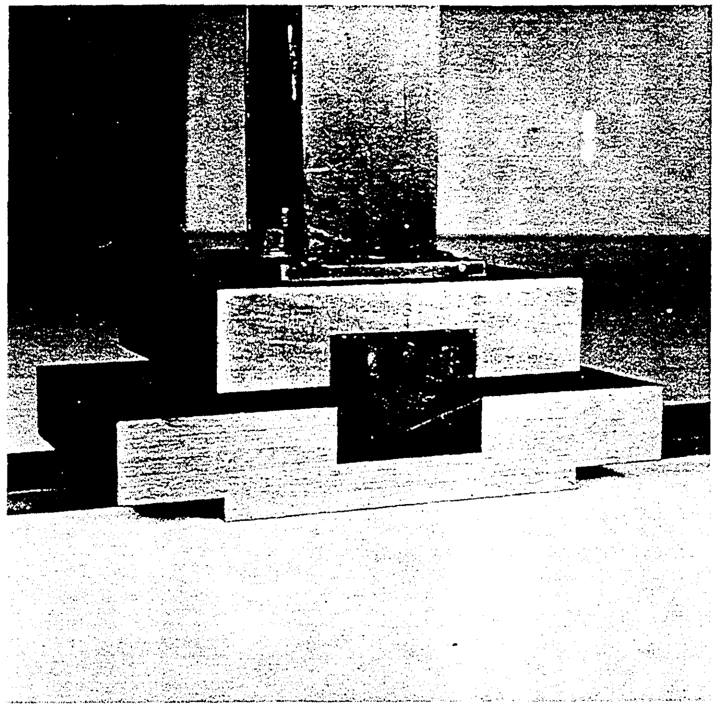


FIG. 30 KNIFE-EDGE SUPPORTS
USED FOR MR MODEL TESTS

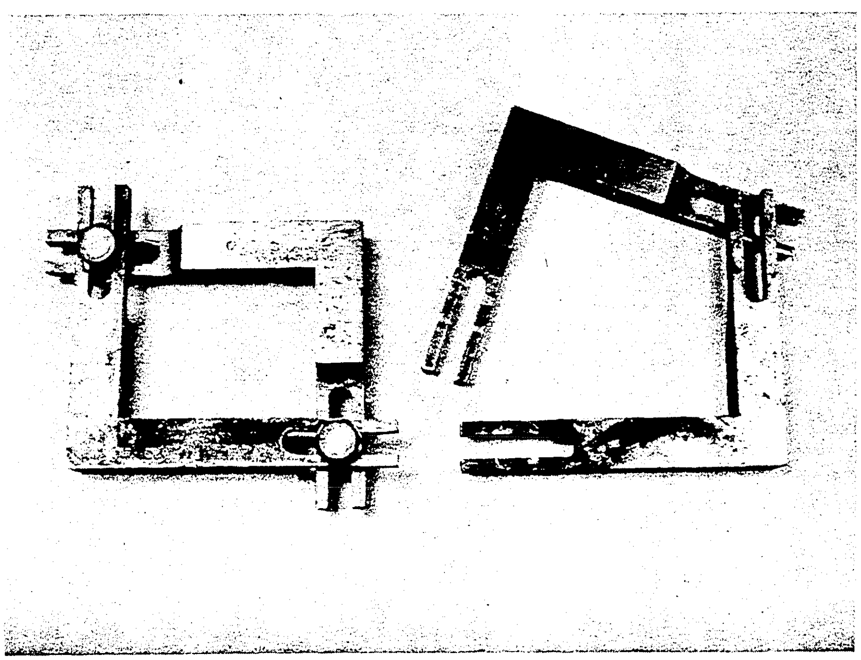


FIG. 31 ADJUSTABLE CLAMPS FOR ASSEMBLING MR MODELS

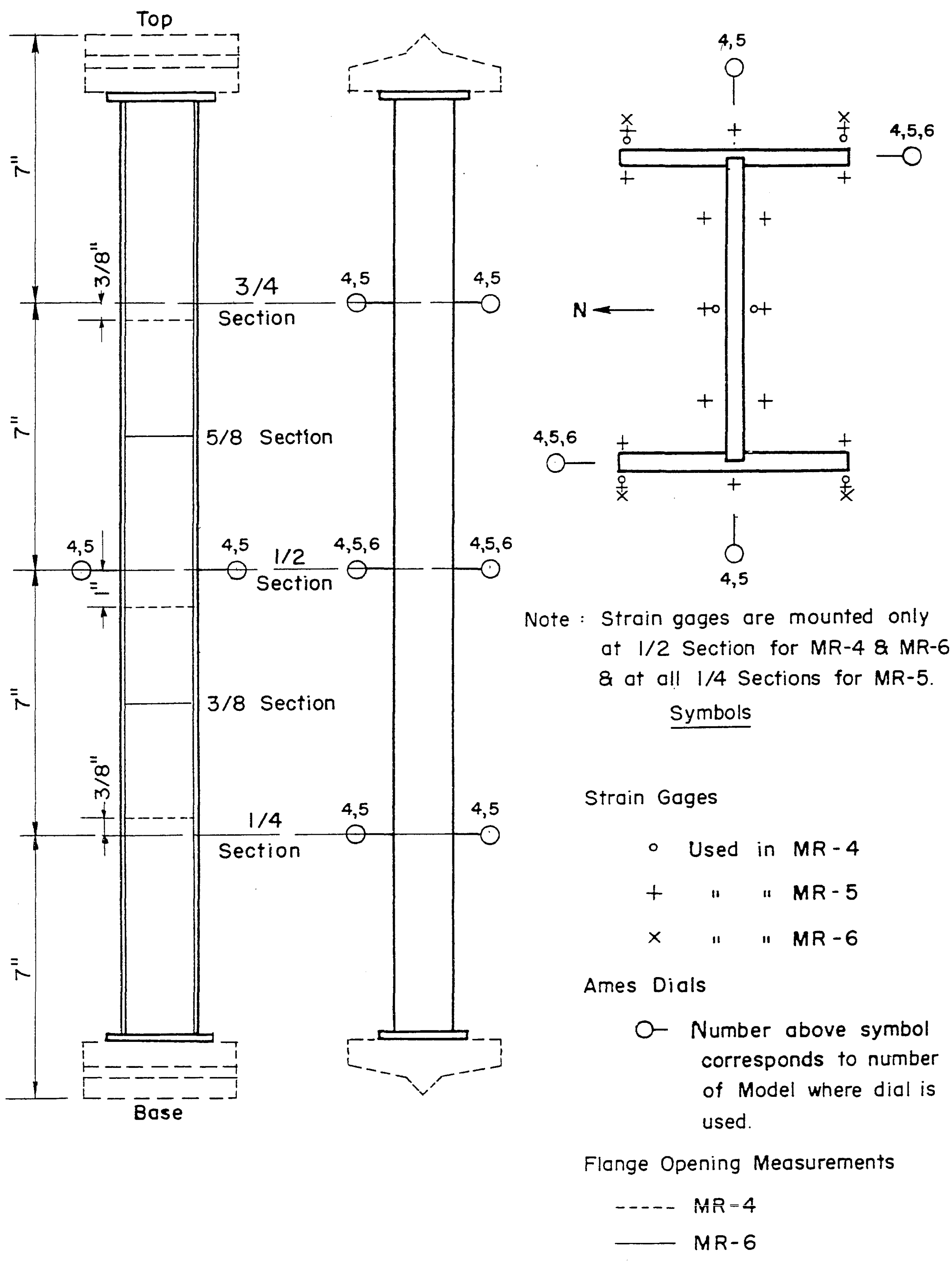


FIG. 32 LOCATION OF STRAIN GAGES AND DEFLECTION MEASUREMENTS FOR MR MODELS

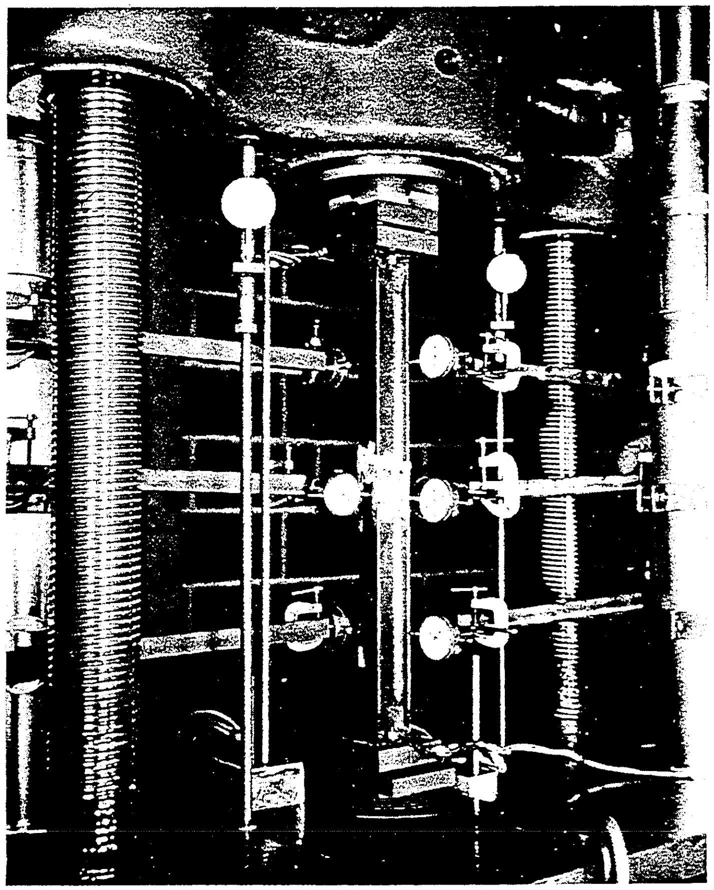


FIG. 33 GENERAL VIEW OF MODEL MR-4
IN TESTING MACHINE

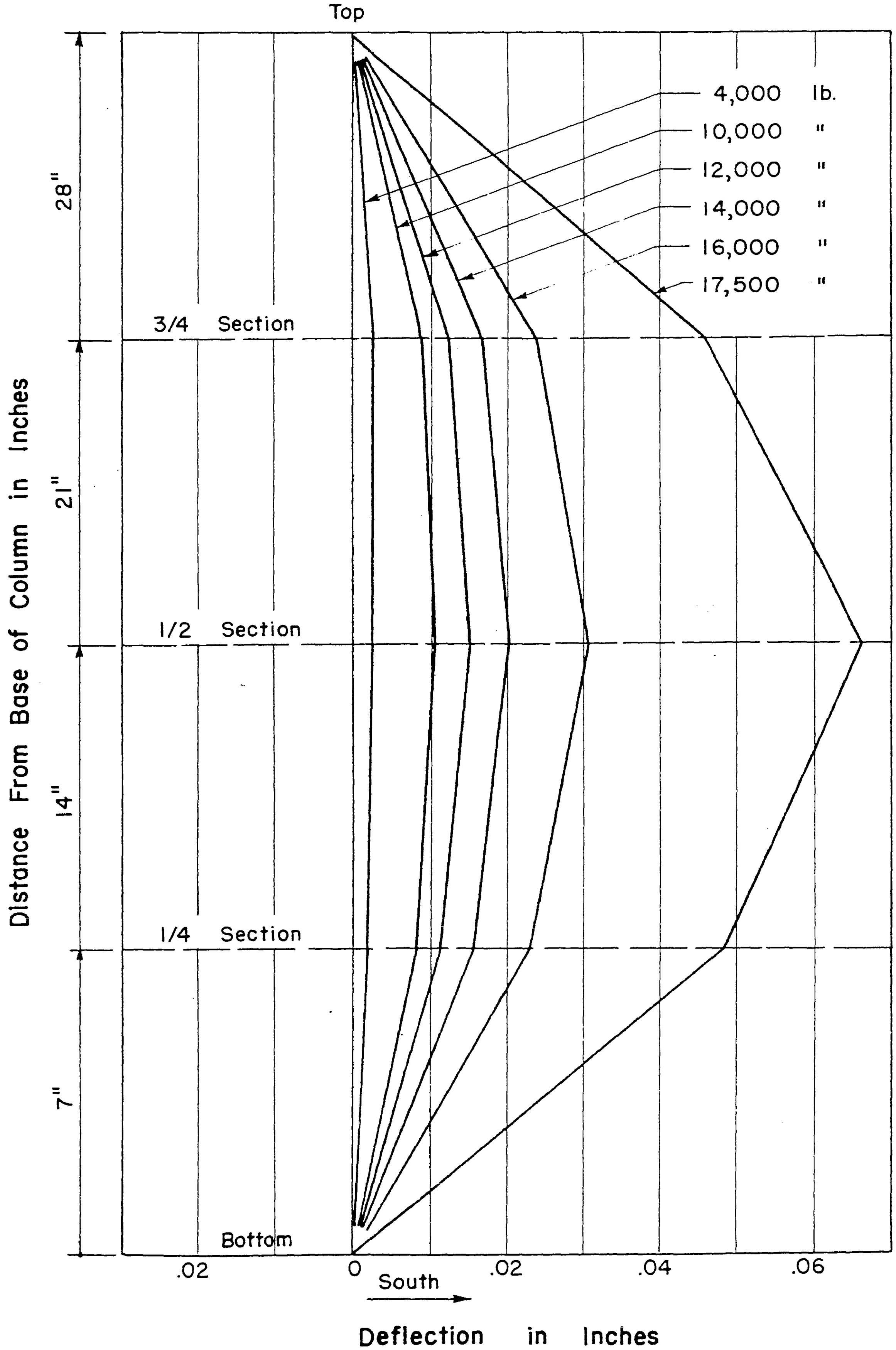


FIG. 34 AVERAGE LATERAL DEFLECTION OF FLANGES IN N-S DIRECTION AT VARIOUS LOADS, MODEL MR-4

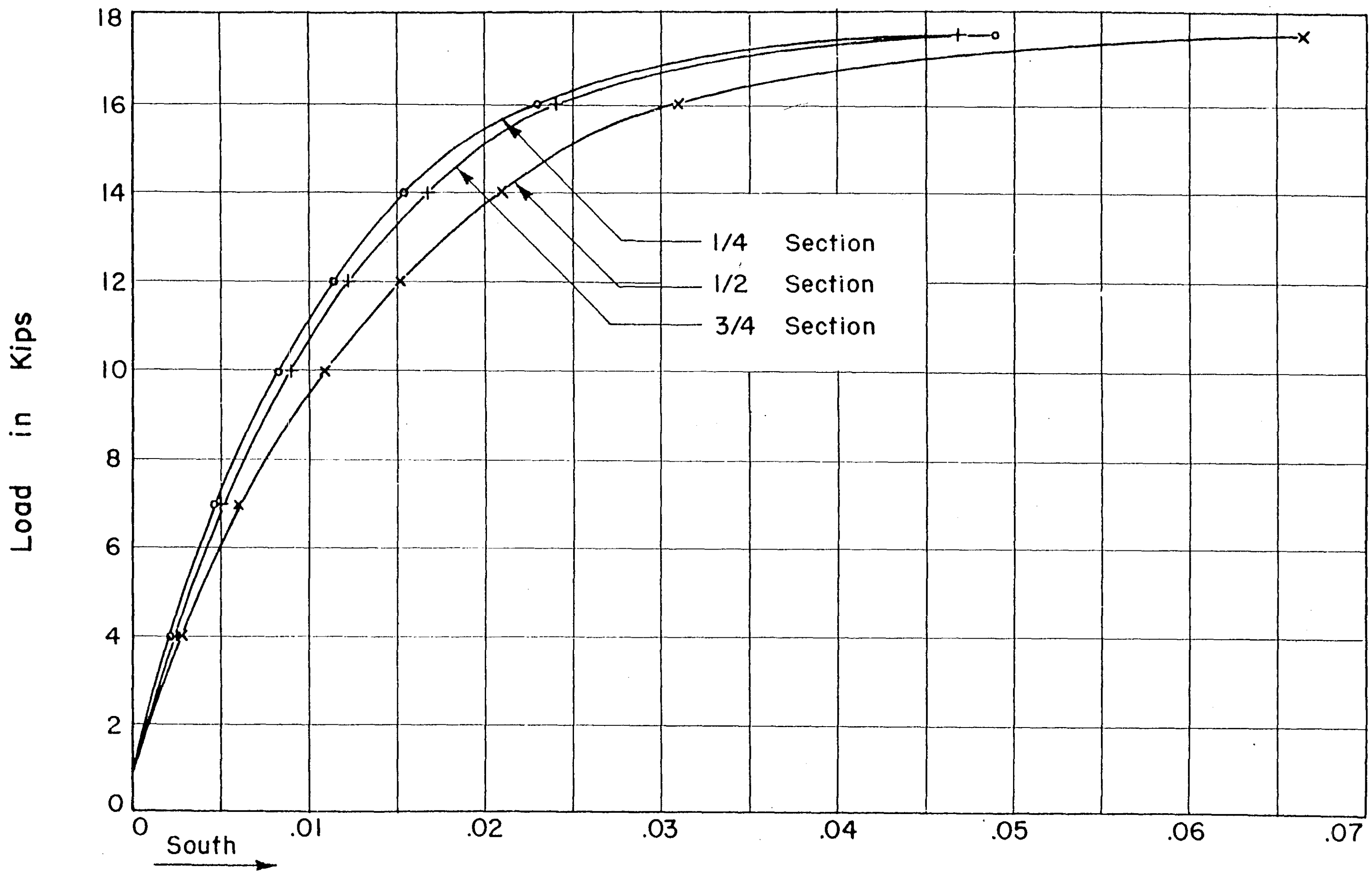


FIG. 35 AVERAGE LATERAL DEFLECTION-LOAD CURVES IN N-S DIRECTION FOR FLANGES OF MODEL MR-4

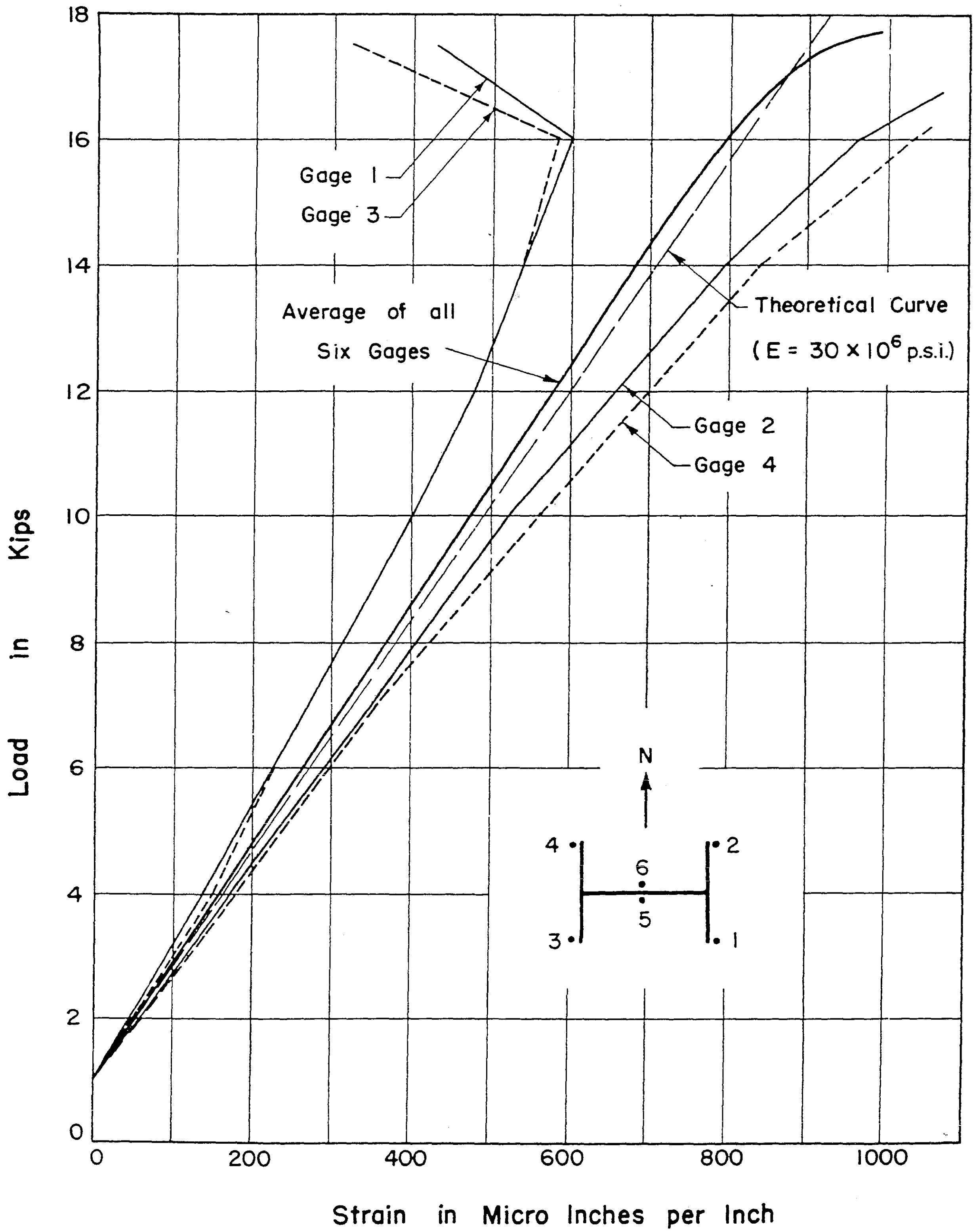


FIG. 36 STRAIN-LOAD CURVES AT MID-HEIGHT OF MODEL MR-4

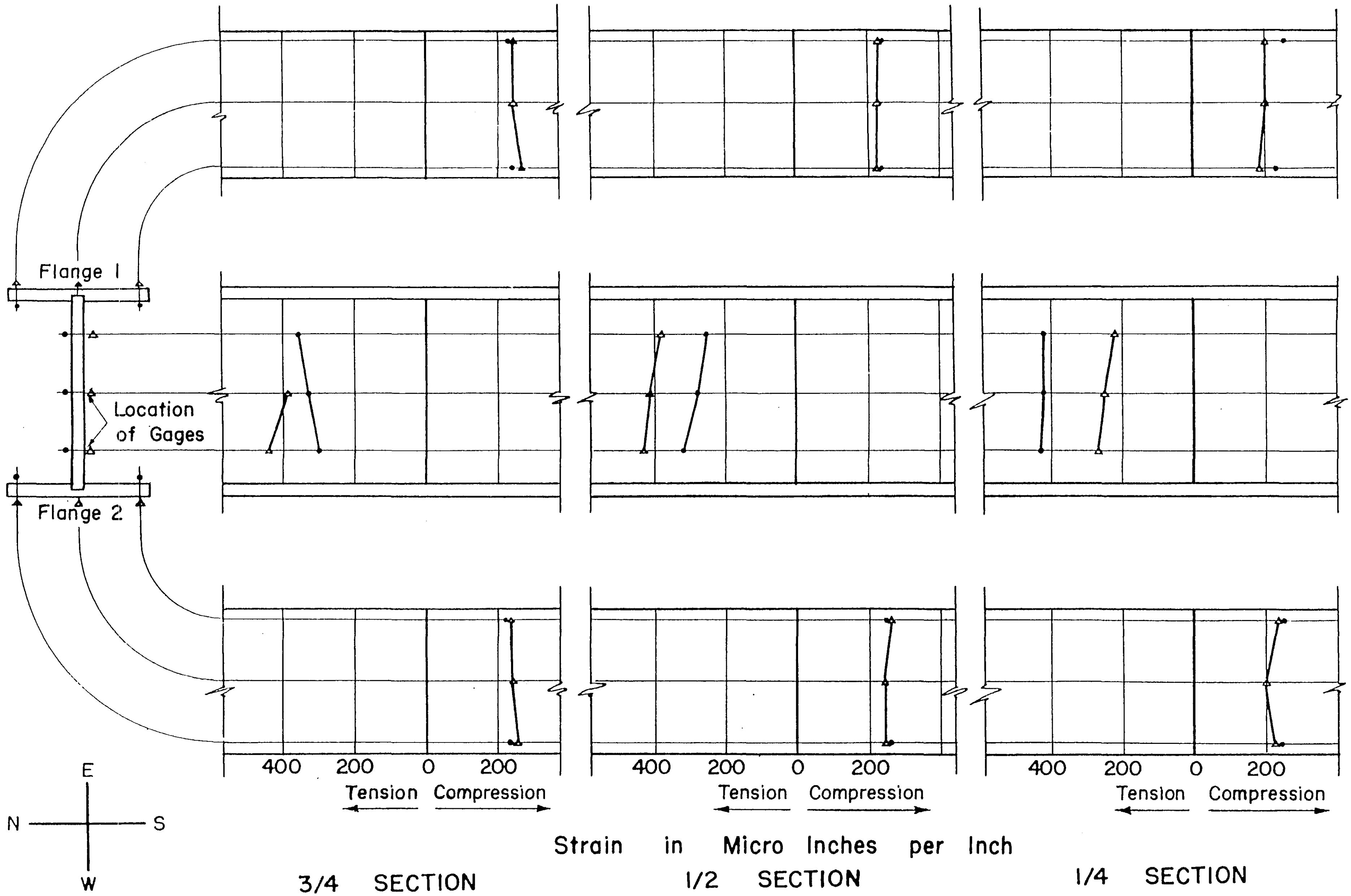


FIG. 39 FINAL RESIDUAL STRAINS IN MODEL MR-5

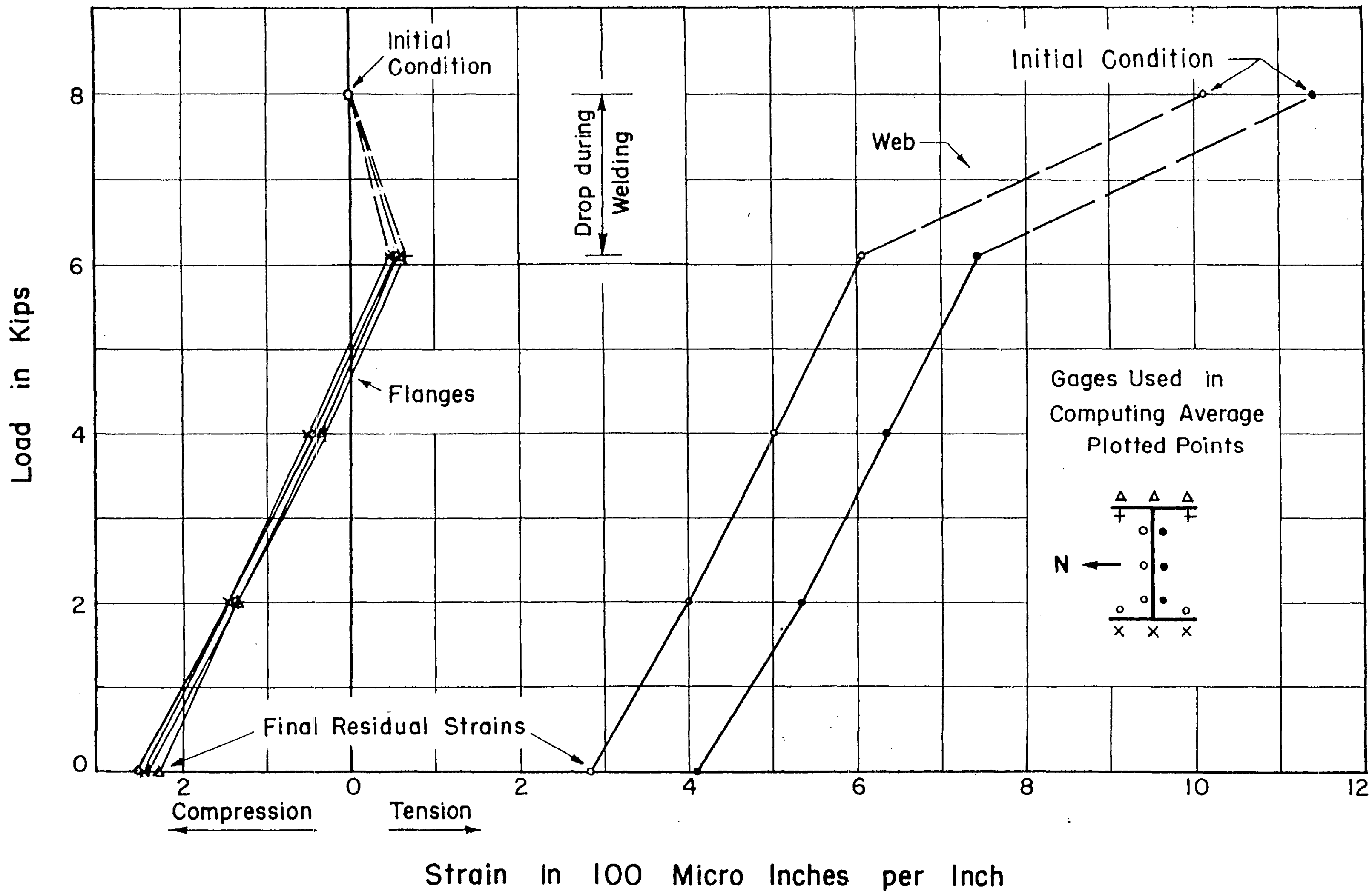


FIG. 40 TYPICAL RESIDUAL STRAIN-LOAD VARIATION AT MID SECTION OF MODEL MR-5 DURING UNLOADING PHASE OF PRESTRESS OPERATION

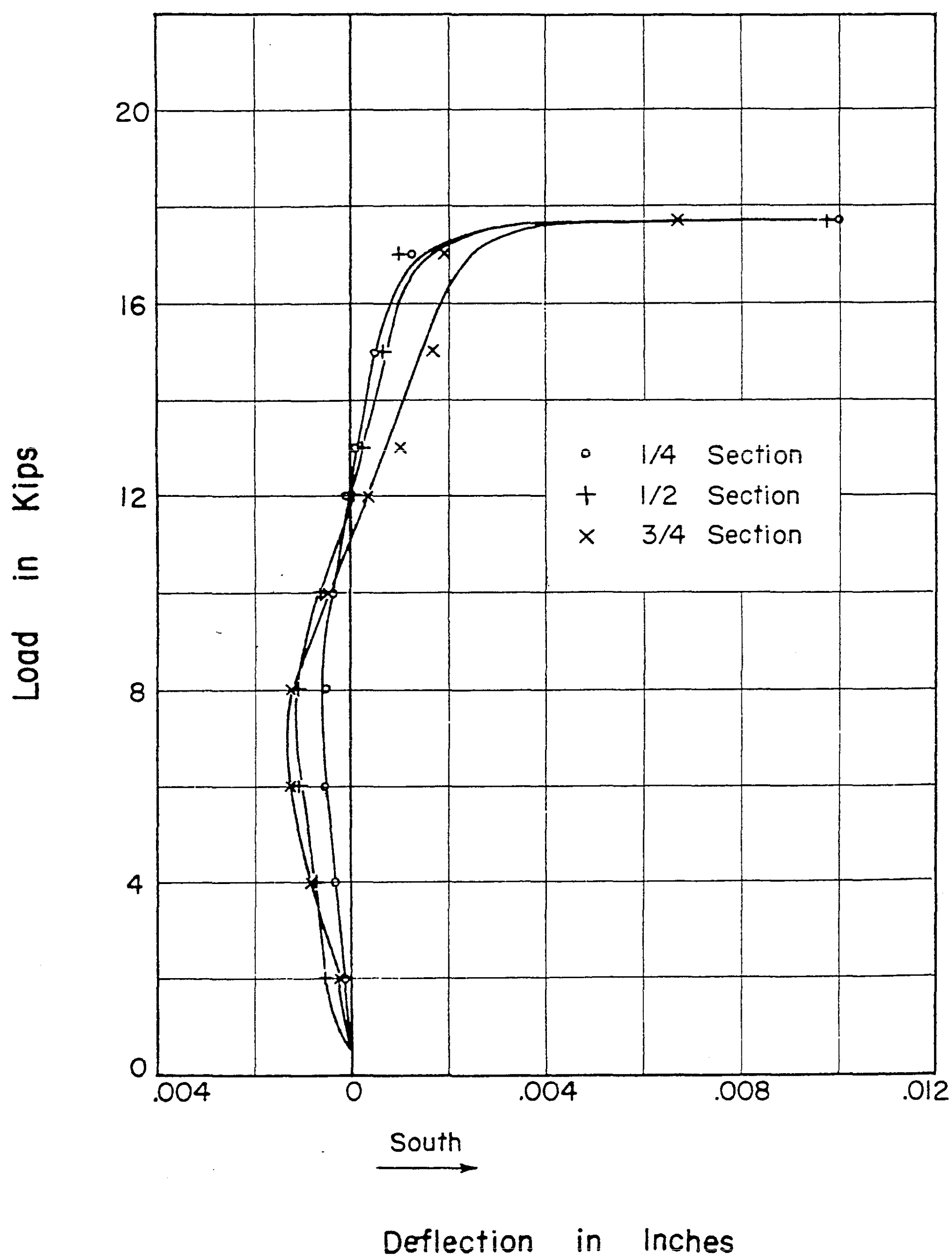


FIG. 41 AVERAGE LATERAL DEFLECTION-LOAD CURVES IN N-S DIRECTION FOR FLANGES OF MODEL MR-5

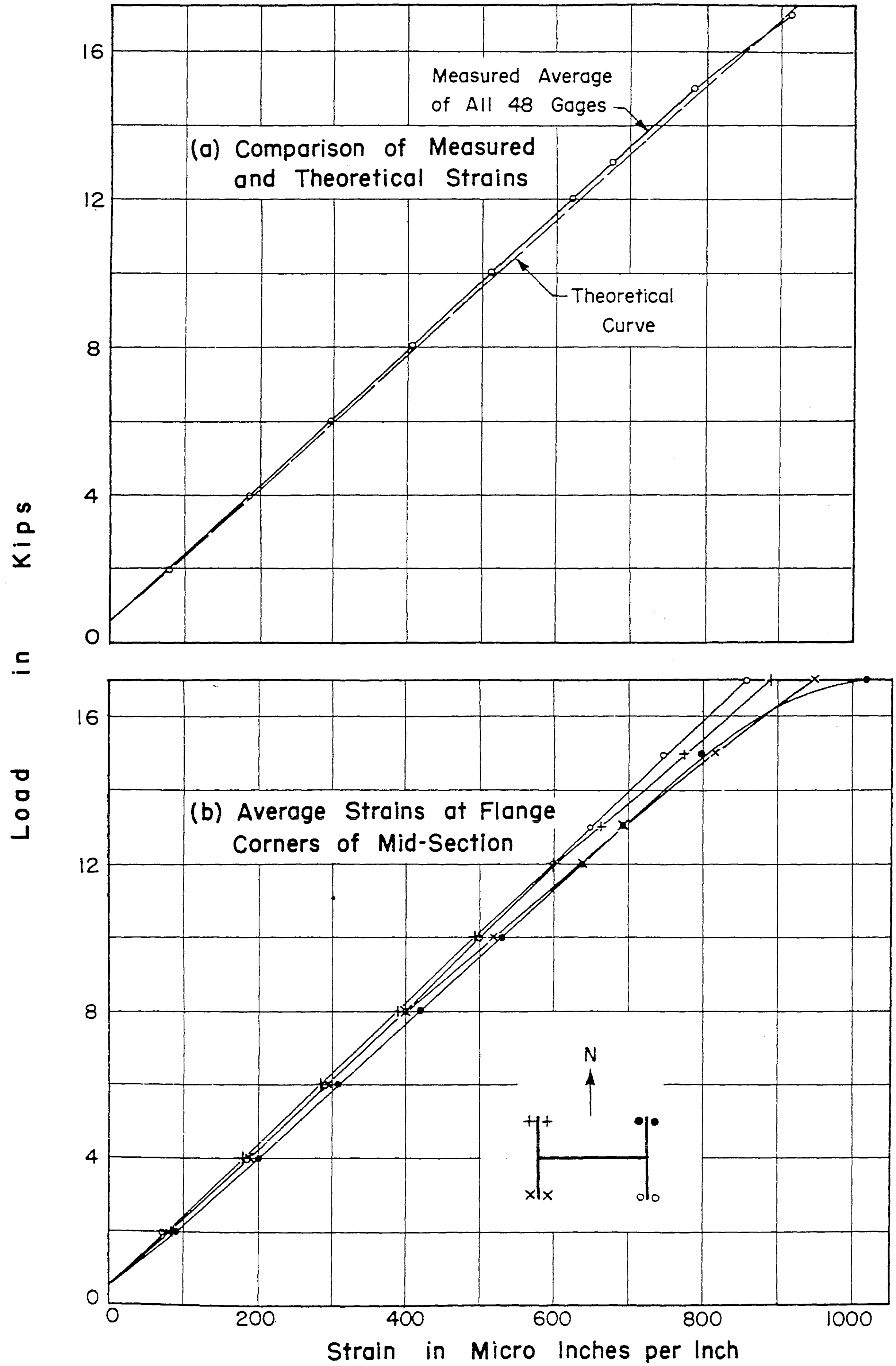
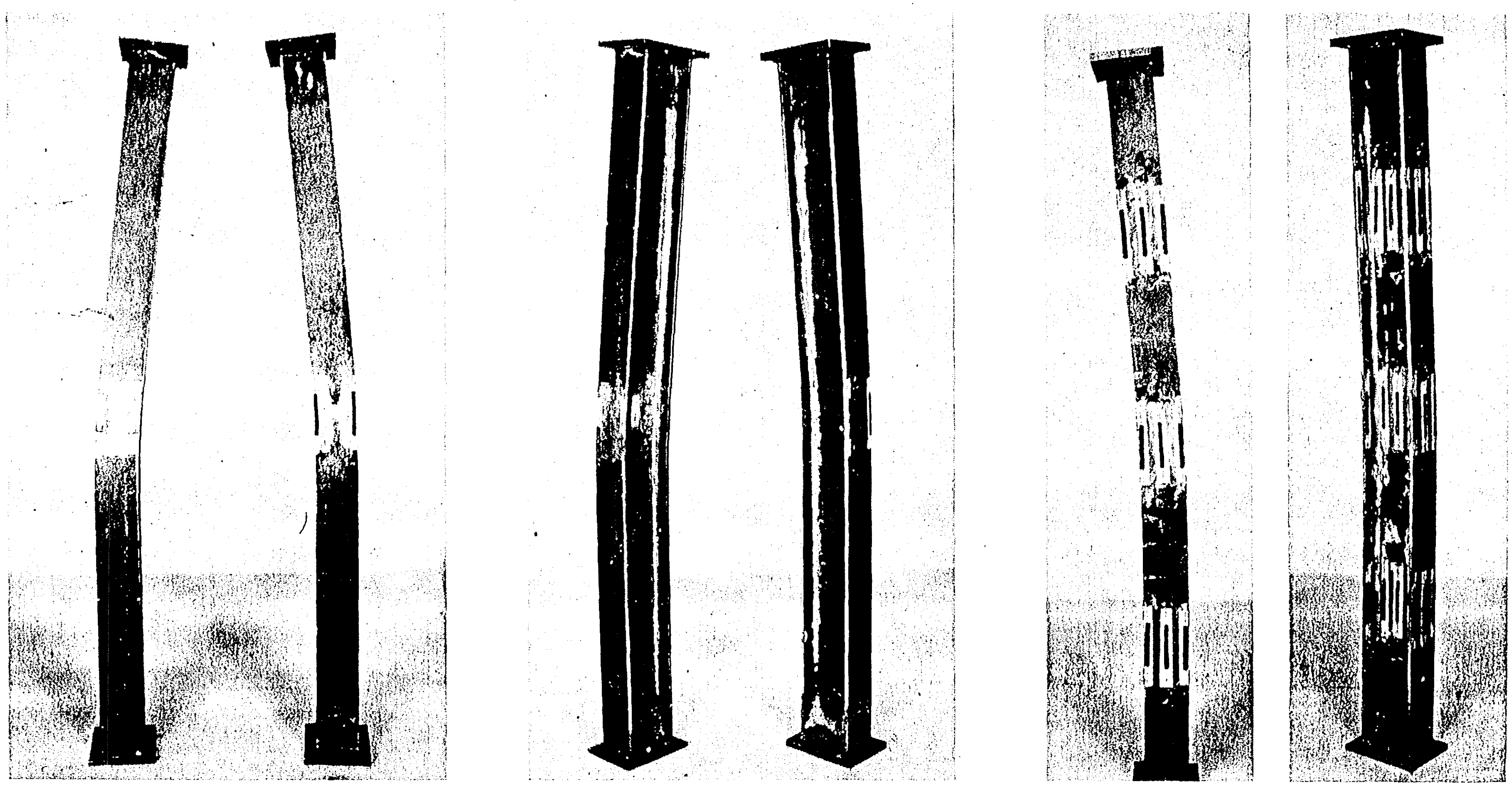


FIG. 42 LOAD-STRAIN CURVES FOR MODEL MR-5



(a) MODEL MR-4 LEFT
MODEL MR-6 RIGHT

(b) MODEL MR-4 LEFT
MODEL MR-6 RIGHT

(c) MODEL MR-5

FIG. 43 MODELS MR-4, MR-5, AND MR-6 AFTER FAILURE

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